DISSERTATION FROM THE
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2018

Sophie E. Steenstrup

Head injuries in FIS World Cup alpine skiers, snowboarders and freestyle skiers

- Epidemiology and video analyses of head impact injury mechanisms

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Oslo Sports Trauma
RESEARCH CENTER

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Errata

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39	However, the relative reduction in the proportion of head injuries was smaller than anticipated (from 18% in 2002 to 15% in 2011).(Sulheim et al., 2017)	Formatting	However, the relative reduction in the proportion of head injuries was smaller than anticipated (from 18% in 2002 to 15% in 2011) (Sulheim et al., 2017).
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93	RICHARDS, D., CARHART, M., SCHER, I., THOMAS, R. & HURLEN, N. 2008. Head Kinematics During Experimental Snowboard Falls: Implications for Snow Helmet Standards.	Reference formatting	RICHARDS, D., CARHART, M., SCHER, I., THOMAS, R. & HURLEN, N. 2008. Head Kinematics During Experimental Snowboard Falls: Implications for Snow Helmet Standards. *Journal of ASTM International*, 5(6)**,** 1-7.
94	SCHER, I., RICHARDS, D. & CARHART, M. 2006. Head Injury in Snowboarding: Evaluating the Protective Role of Helmets.	Reference formatting	SCHER, I., RICHARDS, D. & CARHART, M. 2006. Head Injury in Snowboarding: Evaluating the Protective Role of Helmets. *Journal of ASTM International*, 3(4)**,** 1-9.

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List of papers

This thesis is based on the following original research papers, which are referred to in the text by their Roman numerals:

I. Steenstrup SE, Bere T, Bahr R. Head injuries among FIS World Cup alpine and freestyle skiers and snowboarders: a 7-year cohort study. Br J Sports Med. 2014 Jan;48(1):41-5. doi: 10.1136/bjsports-2013-093145.

II. Steenstrup SE, Bakken A, Bere T, Patton DA, Bahr R. Head injury mechanisms in FIS World Cup alpine and freestyle skiers and snowboarders. Br J Sports Med. 2017 Nov 13. pii: bjsports-2017-098240. doi: 10.1136/bjsports-2017-098240. [Epub ahead of print]

III. Steenstrup SE, Mok KM, McIntosh AS, Bahr R, Krosshaug T. Head impact velocities in FIS World Cup snowboarders and freestyle skiers: Do real-life impacts exceed helmet testing standards? Br J Sports Med. 2017 Jul 8. pii: bjsports-2016-097086. doi: 10.1136/bjsports-2016-097086. [Epub ahead of print]

IV. Steenstrup SE, Mok KM, McIntosh AS, Bahr R, Krosshaug T. Reconstruction of head impacts in FIS World Cup alpine skiing. Br J Sports Med. Published Online First: 25 November 2017. doi: 10.1136/bjsports-2017-098050

Abbreviations

ATD	Anthropomorphic Test Device
CI	Confidence interval
FE	Finite Element
FIS	International Ski Federation
FIS ISS	FIS Injury Surveillance System
MADYMO	Mathematical Dynamical Models
OR	Odds ratio
OWG	Olympic Winter Games
RR	Risk ratio
SD	Standard deviation
TBI	Traumatic Brain Injury
WC	World Cup
WSC	World Ski/Snowboard Championships

Sammendrag

Bakgrunn

Hodeskader representerer et problem blant ski og snowboardutøvere, hvor traumatiske hjerneskader er den hyppigste dødsårsaken. Vi ønsket derfor å beskrive risikoen for hodeskader hos World Cup (WC) ski og snowboardutøvere. Ingen systematisk videoanalyse av mekanismer for hode- og ansiktsskader blant det internasjonale skiforbundets (FIS) WC utøvere er tidligere utført. FIS økte hastigheten for krasjtesting av hjelm fra 5.4 m/s til 6.8 m/s fra 2013/14-sesongen for storslalåm, super-G og utfor, og for freestyle ski cross, men ikke for andre disipliner. Om denne økte testhastigheten reflekterer krasjhastigheter under virkelige skadesituasjoner er uvisst. Vi ønsket derfor å estimere krasjhastigheter ved reelle hodeskadesituasjoner hos FIS WC alpinister, freestyle- og snowboardkjørere. Våre målsetninger var derfor: 1) å beskrive forekomsten av hode/ansiktsskader, 2) beskrive mekanismer for hode/ansiktsskader, og 3) å estimere krasjhastigheter ved reelle hodeskadesituasjoner for å sammenligne krasjkarakteristika med relevante hjelmstandarder.

Metode

Vi utførte retrospektive intervju med FIS WC utøvere i slutten av hver sesong gjennom 10 sesonger (2006-2016), for å registrere skader utøverne hadde pådratt seg i løpet av sesongen. Hodeskader var "hode/ansiktsskader" og inkluderte ikke nakkeskader. Til å beregne eksponering innhentet vi data fra den offisielle resultatdatabasen for alle FIS WC konkurranser for alle de intervjuede utøverne *(Artikkel I)*. Vi innhentet videoer av hode- og ansiktsskader i løpet av 10 WC-sesonger (2006-2016). Vi beskrev hodeskademekanismer ved visuell analyse av 57 videoer av hode- og ansiktsskader (alpint n= 29, snowboard n=13, freestyle n=15) *(Artikkel II)*. Vi analyserte 13 krasj i detalj fra 11 hodeskadevideoer (snowboard n=2, freestyle n=2, alpint n= 7). Et dataprogram ble benyttet til å digitalisere hjelmens bevegelsesbane. Vi estimerte hjelmens bevegelser relatert til omgivelsene, og beregnet endringer i hjelmens hastighet fra før til etter sammenstøtet med snøen (skadetidspunktet). Vi målte også hodets vinkelhastighet i sagittalplanet i 9 krasjsituasjoner *(Artikkel III og IV)*.

Resultater

I løpet av 7 WC sesonger (2006-2013) ble det rapportert 2080 skader. Av disse var 245 (11.8%) hode/ansiktsskader. Hjernerystelse var den hyppigste diagnosen (81.6%), og 58 av disse skadene

var alvorlige (23.7%). Skadeinsidensen per 1000 konkurranseruns var høyest i freestyle (1.8, 95% CI 1.2 til 2.4) sammenlignet med alpint (0.9, 95% CI 0.6 til 1.2; RR 2.05, 95% CI 1.25 til 3.46) og snowboard (1.0, 95% CI 0.6 til 1.3; RR 1.85, 95% CI 1.15 til 2.99). Kvinner hadde høyere skadeinsidens (5.8, 95% CI 4.8 til 6.9) sammenlignest med menn (3.9, 95% CI 3.2 til 4.6; RR 1.48, 95% CI 1.15 til 1.90) per 100 utøvere *(Artikkel I).* Vi identifiserte en felles krasjsekvens i alle disipliner, hvor 84% av utøverne kontaktet underlaget med skiene eller brettet først, etterfulgt av ekstremitetene, hoftene/bekkenet, ryggen og, til sist, hodet. Alpinistene falt sidelengs (45%) eller bakover (35%) med slag baktil (38%) og på siden (35%) av hjelmen. Freestylekjørere og snowboardere falt bakover (snowboard 77%, freestyle 53%), med slag hovedsakelig baktil på hjelmen (snowboard 69%, freestyle 40%). Blant alpinistene var det 3 tilfeller (10%) hvor hjelmen falt av, og 41% av skadene blant alpinistene skjedde som følge av uhensiktsmessig portkontakt. Under krasjsekvensen i alle disipliner fikk utøverne hovedsakelig ett (47%) eller to (28%) slag mot hodet, og hodet traff fortrinnsvis snøen (83%) *(Artikkel II).* I 11 av 13 hodeskadesituasjoner, var den estimerte hastigheten til hodet vinkelrett på bakken umiddelbart forut for krasjet høyere enn den nåværende FIS hjelmstandarden på 6.8 m/s (gennomsnitt 8.3 ± SD 2.6 m/s, fra 1.9 ± 0.8 m/s til 12.1 ± 0.4 m/s). Hodets gjennomsnittlige hastighetsforandring vinkelrett på bakken for de 13 krasjsituasjonene var 9.6 ± 2.3 m/s (fra 5.2 ± 1.1 m/s til 13.5 ± 1.3 m/s). I sagittalplanet gjennomgikk hodet en stor forandring i vinkelhastighet (gjennomsnitt 40.2 ±15.1 rad/s, fra 21.2 ± 1.5 rad/s til 64.2 ± 3.0 rad/s) under krasjet *(Artikkel III og IV).*

Perspektiver

Vi har beskrevet forekomsten av, og mekanismer for, hode/ansiktsskader, samt estimert hodets krasjhastighet i alpint, snowboard og freestyle. Dette er viktig informasjon hvis hjelmtesting skal utvikles for å etterligne realistiske krasjsituasjoner. Fremtidige laboratorie- eller feltbaserte studier bør undersøke snøegenskaper og utføre krasjtester av hjelm på snø, for å bedre forstå hvordan krasjsituasjoner på snø samsvarer med testing i et laboratorium. Videre forskning på hodeskader og hjelmstandarder i alle disipliner er nødvendig. I fremtiden bør forebyggende tiltak rettes mot å unngå alvorlige hodeskader i alle displiner, tilstrekkelig medisinsk oppfølging for alle hodeskader, og oppfølging av både kvinnelige og mannlige freestyle og snowboardutøvere. Sikkerhet for utøverne kan potensielt forbedres gjennom løypedesign, med fokus på hoppkonstruksjoner og reduksjon av fart i alpint, spesielt i svinger og terrengoverganger. Videreutvikling av utløsermekanismer for portflagg anbefales, og fokus på korrekt hjelmbruk og tilpasning av hjelm er viktig for å forhindre fremtidige situasjoner hvor hjelmen faller av.

Summary

Background

Head injuries represent a concern in skiing and snowboarding, where traumatic brain injury is the most common cause of death. We therefore wanted to describe the risk of head injuries across disciplines and sex among World Cup (WC) skiers and snowboarders. No systematic video analysis of head/face injury mechanisms at the WC level has been conducted. Prior to the 2013/14 season the International Ski Federation (FIS) increased the helmet testing speed from 5.4 m/s to 6.8 m/s for alpine downhill, super-G and giant slalom, and for freestyle ski cross, but not for other disciplines. Whether this increased testing speed reflects impact velocities in real head injury situations on snow is unclear. Therefore, our aims were to describe: 1) the epidemiology of head/face injuries, 2) the gross mechanisms of head/face injuries, and 3) the gross head impact biomechanics, to compare the head impact characteristics with relevant helmet standards.

Methods

We conducted retrospective interviews with FIS WC athletes at the end of 10 consecutive seasons (2006-2016), to register injuries sustained during the competitive season. We collected injury videos at the end of each season. Head injuries were classified as "head/face" injuries and did not include neck or cervical spine injuries. To calculate the exposure, we extracted data from the official FIS results database for all WC competitions for each of the athletes interviewed *(Paper I)*. We performed a qualitative visual analysis of videos of head and face injuries reported through the FIS ISS during 10 WC seasons (2006-2016), to describe gross head injury mechanisms. We analysed 57 head impact injury videos (alpine n= 29, snowboard n=13, freestyle n=15) *(Paper II)*. We reconstructed 13 head impacts in total from 11 broadcast head injury videos (snowboard n=2, freestyle n=2, alpine n= 7) in detail. We used video-based motion analysis software to estimate head impact kinematics in two dimensions, including directly preimpact and postimpact, from the broadcast videos. The sagittal plane angular movement of the head in 9 impacts was also measured using angle measurement software *(Papers III and IV)*.

Results

During 7 WC seasons (2006-2013), 2080 injuries were reported. Of these, 245 (11.8%) were head/face injuries; nervous system injuries/concussions were the most common (81.6%) and 58

of these were severe (23.7%). The injury incidence per 1000 competition runs was higher in freestyle (1.8, 95% CI 1.2 to 2.4) than in alpine skiing (0.9, 95% CI 0.6 to 1.2; RR 2.05, 95% CI 1.25 to 3.46) and snowboard (1.0, 95% CI 0.6 to 1.3; RR 1.85, 95% CI 1.15 to 2.99). Females had a higher injury incidence (5.8, 95%CI 4.8 to 6.9) vs. males (3.9, 95% CI 3.2 to 4.6; RR 1.48, 95% CI 1.15 to 1.90) throughout the season (per 100 athletes) *(Paper I)*. During the crash sequence, most athletes (84%) impacted the snow with the skis or board first, followed by the upper or lower extremities, buttocks/pelvis, back and, finally, the head *(Paper II)*. Alpine skiers had sideways (45%) and backwards pitching falls (35%), with impacts to the rear (38%) and side (35%) of the helmet. Freestyle skiers and snowboarders had backwards pitching falls (snowboard 77%, freestyle 53%), mainly with impacts to the rear of the helmet (snowboard 69%, freestyle 40%). There were three helmet ejections among alpine skiers (10%), and 41% of alpine injuries occurred due to inappropriate gate contact prior to falling. Athletes had one (47%) or two (28%) head impacts, mainly on snow (83%) *(Paper II)*. In 11 of 13 head impacts, the estimated normal-to-slope preimpact velocity was higher than the current FIS helmet rule of 6.8 m/s (mean 8.3 ± 2.6 m/s, range 1.9 ± 0.8 m/s to 12.1 ± 0.4 m/s). The 13 head impacts had a mean normal-to-slope velocity change of 9.6 ± 2.3 m/s (range 5.2 ± 1.1 m/s to 13.5 ± 1.3 m/s). There was a large change in sagittal plane angular velocity (mean 40.2 ±15.1 rad/s, range 21.2 ± 1.5 rad/s to 64.2 ± 3.0 rad/s) during impact *(Papers III and IV)*.

Perspectives

In addition to the incidence of head/face injury, we have provided important information about real gross head injury mechanisms and gross head impact biomechanics in alpine, snowboarding and freestyle skiing, which are important considerations if helmet testing is to be developed and evaluated under realistic impact conditions. Future laboratory or field based studies should examine snow properties and perform helmet impact tests on real-life snow, to increase our understanding of the equivalence between real head impacts on snow and impacts in a laboratory. Continued research into head injuries and helmet standards in all disciplines is needed. Future prevention strategies should address severe injuries across all disciplines, promote adequate recognition and medical attention for all head injuries, and target freestyle and snowboarding athletes, with at least equal attention to female athletes. Safety for the athletes may improve by improvements in course design, focusing on safe jump constructions, and reducing alpine skier speeds, especially during turns and terrain transitions. Further research into the optimal design of release gate panels and poles should continue, and helmet fit and wearing correctness must be adressed to prevent future helmet ejections.

Introduction

To prevent head injuries among athletes, knowledge about why and how injuries occur is needed (van Mechelen et al., 1992). van Mechelen et al. (1992) proposed a four step injury prevention model where, firstly, the extent of the injury problem must be identified and described (van Mechelen et al., 1992). Secondly, the factors and mechanisms which play a part in the occurrence of head injuries have to be identified. The third step is to introduce measures that are likely to reduce the future risk and/or severity of head injuries. This measure should be based on the aetiological factors and the mechanisms as identified in the second step. Finally, the effect of the measures must be evaluated by repeating the first step (Figure 1) (van Mechelen et al., 1992).

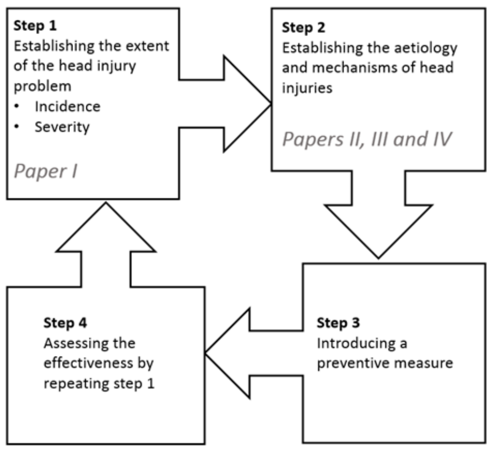

Figure 1*. The four step injury prevention model. Adapted from van Mechelen et al. 1992.*

This PhD thesis relates to the first and second step of the van Mechelen four-step injury prevention model, and will therefore specifically cover the following two aims:

1. Establish the incidence and severity of head injuries among FIS WC alpine and freestyle skiers and snowboarders (Step 1, *Paper I*)

2. Describe gross head injury mechanisms and gross head impact biomechanics among these athletes, using qualitative and quantitative video analyses (Step 2, *Papers II, III and IV*).

Causes of injuries: risk factors and injury mechanisms

A critical step in the four-step injury prevention process is to establish the causes of injuries (step 2, Figure 1) (van Mechelen et al., 1992). This includes obtaining information about why a particular athlete may be at risk in a given situation (risk factors), and how injuries occur (injury mechanisms) (Bahr and Krosshaug, 2005). Firstly, one must identify those factors associated with an increased risk of injury.

Risk factors

According to the risk factor assessment model developed by Meeuwisse in 1994, risk factors may influence the risk of sustaining an injury or predispose the athlete to injury (Meeuwisse, 1994). These risk factors are termed internal or external risk factors. Internal risk factors are part of the athlete's constitution that may make them predisposed to injury (Meeuwisse, 1994). For example, possible internal risk factors related to sports-related concussion could be the amount of cerebral blood flow, cerebrospinal fluid volume, hydration status, fatigue, sleep deprivation and concurrent illness (Broglio et al., 2012). Athletes are exposed to external risk factors when they participate in training or competitions, which may make them susceptible to injury (Meeuwisse, 1994). External risk factors make the athletes susceptible to injury, and can be opponents on a course in eg. snowboard cross, use of protective equipment (such as wearable airbags and helmets), equipment such as the skis or snowboard (which could e.g. potentially increase the load on the knee joints in twisting situations), the exposure (such as the number of runs or skiing days) and the environment (such as wind, visibility or snow conditions). Of particular relevance to this thesis, is the potential for a helmet to be both protective and/or an external risk factor for injury. This will therefore be discussed extensively in the chapter "Head injury prevention" (p. 35). According to Meeuwisse (1994) a risk factor may be part of, or a collection of factors that together produce a sufficient cause for an injury to occur. In other words, the reasons for injuries are mulifactorial (Meeuwisse, 1994).

Injury mechanisms

To present a thorough description of injury mechanisms, Bahr & Krosshaug (2005) described a broad model for injury causation (Bahr and Krosshaug, 2005). This model was based on the epidemiological model of Meeuwisse (1994), and included a biomechanical perspective, such as describing the whole body and joint biomechanics at the time of injury, in addition to focusing on the characteristics of the sport in question (Figure 2) (Bahr and Krosshaug, 2005).

As exemplified by this model, a predisposed athlete inhabits certain internal risk factors, which coupled with exposure to certain external risk factors, makes the athlete susceptible to injury. However, for the injury to occur, there must also be an inciting event, i.e. there must be an injury causing mechanism. According to Meeuwisse (1994), the inciting event is the final link in the chain that causes the injury.

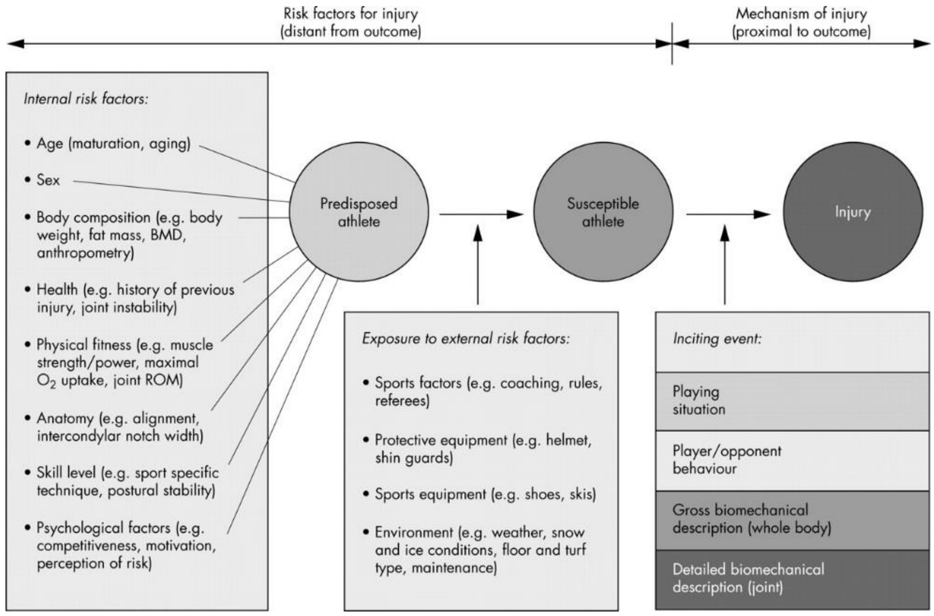

Figure 2. *From Bahr & Krosshaug 2005. Reproduced with permission from BMJ Publishing Group Ltd. 08.11.2017*

The FIS Injury Surveillance System

Establishing reliable systems for injury surveillance is a key risk management tool (Dick et al., 2007). Such recording systems represent the first and last step in the four-step sequence of injury prevention research (Figure 1) (van Mechelen et al., 1992). The FIS Injury Surveillance System (FIS ISS) was therefore developed prior the 2006/2007 winter season by FIS in collaboration with the Oslo Sports Trauma Research Center (OSTRC) (Flørenes et al., 2011). The purpose of the FIS ISS was firstly to monitor injury patterns and trends in the different FIS disciplines (alpine skiing, freestyle skiing, snowboarding and ski jumping) and secondly to provide background data for in-depth studies of the causes of injury. The ultimate objective is to reduce the risk of injuries among the athletes by suggesting preventive measures for the future (Flørenes et al., 2011).

In recreational skiing and snowboarding, different methods such as reports from ski patrols, physicians at base-lodge clinics, hospital reports or self-reports have been used to record injuries (Flørenes et al., 2011). In general, prospective cohort studies are recommended to monitor injury patterns and risk over time (Fuller et al., 2006). However, as it was not known which method would yield the most complete and accurate record of injuries to WC ski and snowboard athletes, Flørenes et al. (2011) evaluated in a methodological study what would be the best method to register injuries in this athlete population. The information sources potentially available were the athletes themselves, their medical staff or the technical delegate (TD). Flørenes et al. (2011) reported that retrospective interviews with athletes and coaches regarding injuries during the competitive winter season gave the most complete picture of injuries to WC skiers and snowboarders compared to the two other options. Therefore, retrospective athlete/coach interviews at the end of every WC season became the preferred method in the FIS ISS (Flørenes et al., 2011). All medical information regarding included athletes in this project was obtained through the FIS ISS. This head injury data provides background data for further in-depth studies into the mechanisms of head injuries among WC athletes.

Head injuries

Head injuries are injuries to the scalp, skull, or brain caused by trauma (Bahr, 2014). Skull fractures and brain injuries result from physical loads to the head (Stemper and Pintar, 2014). The International Classification of Disease, 10th edition 2017 (ICD-10) is a medical classification system by the World Health Organization (WHO) (http://www.icd10data.com/ICD10CM/Codes/S00-T88/S00-S09).

It contains codes for diseases, signs and symptoms, abnormal findings, complaints, social circumstances, and external causes of injury or diseases. According to the ICD-10 diagnosis codes, a head injury is:

S00 Superficial injury of head, S01 Open wound of head, S02 Fracture of skull and facial bones, S03 Dislocation and sprain of joints and ligaments of head, S04 Injury of cranial nerve, S05 Injury of eye and orbit, S06 Intracranial injury, S07 Crushing injury of head, S08 Avulsion and traumatic amputation of part of head, and S09 Other and unspecified injuries of head.

Because Traumatic Brain Injuries (TBIs), including concussions, are the most common in skiing and snowboarding, brain injuries and their mechanisms will be discussed further (Sharma et al., 2015, Levy et al., 2002). Therefore, according to the ICD-10 codes, most injuries discussed in this thesis will belong to the ICD-10 code S06 Intracranial injury. However, as discussed later (p. 45), the FIS ISS uses a classification of injury and injury severity based on a consensus document on general injury surveillance in football, and is therefore not a head-injury specific classification system (Fuller et al., 2006).

Genarelli (1993) described two categories of brain injury: focal injuries and diffuse injuries. Focal brain injuries, which are usually caused by direct blows to the head, comprise contusions, brain lacerations, and hemorrhage leading to the formation of hematoma in the extradural, subarachnoid, subdural, or intracerebral compartments within the head (Gennarelli, 1993). Diffuse brain injuries, which are usually caused by a sudden movement of the head, comprise concussion and more prolonged posttraumatic coma, also known as diffuse axonal injury (Gennarelli, 1993, Ommaya and Gennarelli, 1974). In sports, TBIs commonly result from impact to the head leading to a high head acceleration or deceleration (Stemper and Pintar, 2014). Thus, in skiers and snowboarders, according to the categories decribed by Genarelli (1993), it is reasonable to assume that athletes can suffer both focal and diffuse brain injuries (Gennarelli, 1993).

Sports-related concussion

According to the Berlin 2017 Consensus statement on concussion in sport (McCrory et al., 2017) a Sports-Related Concussion (SRC) is:

"*Sports-related concussion is a traumatic brain injury induced by biomechanical forces. Several common features that may be utilised in clinically defining the nature of a concussive head injury include:*

- *SRC may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head*
- *SRC typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, in some cases, signs and symptoms evolve over a number of minutes to hours*
- *SRC may result in neuropathological changes, but the acute clinical signs and symptoms largely reflect a functional disturbance rather than a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies.*
- *SRC results in a range of clinical signs and symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive features typically follows a sequential course. However, in some cases symptoms may be prolonged (McCrory et al., 2017).*"

The term mild traumatic brain injury (mTBI) is often used interchangeably with concussion; however, this term is vague and not based on validated criteria in this context (McCrory et al., 2017). One unresolved issue is whether concussion is part of a TBI spectrum associated with lesser degrees of diffuse structural change than are seen in severe TBI, or whether the concussive injury is the result of reversible physiological changes (McCrory et al., 2017). Figure 4 illustrates the assumed relationship between TBI and sports related concussion on a severity spectrum based on the Glasgow Coma Scale (GCS). The GCS is the most common scoring system used to describe the level of consciousness in a person following TBI (Teasdale and Jennett, 1974, Teasdale et al., 2014). The GCS rates the severity of brain injury as mild (GCS 13-15), moderate (GCS 9-12) and severe (GCS ≤8) (Teasdale and Jennett, 1974).

Traumatic brain injury (TBI)

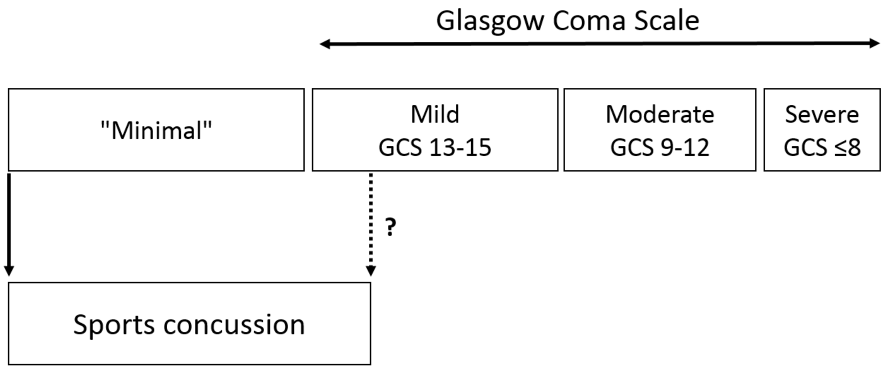

Figure 4. *The assumed severity spectrum of typical sports concussions in relation to traumatic brain injuries graded in severity with the GCS. Adapted from the Concussion in Sport Group (2017) (McCrory et al., 2017) and Teasdale and Jennett (1974).*

Severe sports-related traumatic brain injuries

Severe sports-related head injuries include acute subdural hematoma, acute epidural hematoma, cerebral contusion, traumatic cerebrovascular accidents, diffuse brain swelling, diffuse axonal injury and skull fractures (Nagahiro and Mizobuchi, 2014). Acute subdural hematoma is a leading cause of death and severe morbidity in general, and in American football, judo, boxing and snowboarding, especially, and may be the most common intracranial pathology in snowboarders (Nakaguchi et al., 1999, Fukuda et al., 2001, Nagahiro and Mizobuchi, 2014).

Acute subdural hematoma is an abnormal collection of blood that layers between the fibrous covering of the brain known as the dura and the brain itself, and usually occurs due to rapid acceleration and deceleration, which ruptures small veins between the brain and dura, specifically a bridging vein or veins (Miller and Nader, 2014, Bahr, 2014, Gennarelli and Thibault, 1982). The anatomy of the bridging vein predisposes to its tearing within the border cell layer of the dura mater (Miller and Nader, 2014). Gennarelli and Thibault (1982) described that acute subdural hematoma due to ruptured bridging veins occurrred under acceleration conditions due to the strain-rate sensitivity of the bridging veins. As a consequence of the ruptured veins, the subdural hematoma forms within the dura (Miller and Nader, 2014).

In general, the clinical causes of acute subdural hematoma have been reported to be due to high-strain falls and assaults (72%) or due to lower strain-rate vehicular injuries (24%) (Gennarelli and Thibault, 1982). In judo, many catastrophic head injuries occurred when players were thrown to the judo mat on their back without managing to dampen the fall (Kamitani et al., 2013). If the rotational acceleration force on the head cannot be dissipated by dampening the fall, and the back of the skull strikes the mat, the brain will continue to move inside the skull because of the moment of inertia, creating a gap between the brain and dura, rupturing the bridging vein, and resulting in acute subdural hematoma (Kamitani et al., 2013). Nagahiro and Mizobuchi (2014) therefore discussed that rotational acceleration is most likely to produce not only cerebral concussion but also acute subdural hematoma due to the rupture of a bridging vein, depending on the severity of the rotational acceleration injury (Nagahiro and Mizobuchi, 2014).

Based on findings from hospital reports and CT scans, in severely head-injured recreational snowboarders, the risk factors most likely to cause an acute subdural hematoma were falls, impacts to the occipital region, falling backwards (back-edge catch), and falls on a mild slope (Nakaguchi and Tsutsumi, 2002).

However, it is also important to consider that chronic subdural hematoma can occur after head impacts that do not seem severe at the time of the crash. Two medical case reports have described the development of chronic subdural hematoma in snowboarders (Rajan and Zellweger, 2004, Uzura et al., 2003). Uzura et al. (2003) presented two snowboarding cases, where the initial head impacts were mild, and the patients had no symptoms immediately post-impact (Uzura et al., 2003). The first case fell backwards on a steep slope while snowboarding and impacted the occiput on the snow, while the second case impacted his right temporal area after a crash during jumping (Uzura et al., 2003). The chronic subdural hematomas were discovered on CT scans five and six weeks post-impact (Uzura et al., 2003). Rajan & Zellweger (2004) described a 26 year-old professional snowboarder, who had developed an enormous left-sided subdural haematoma, with a major midline shift and compression of the left lateral ventricle and hemisphere, after two unexceptional head impacts during half pipe training, two months previously (Figure 5).

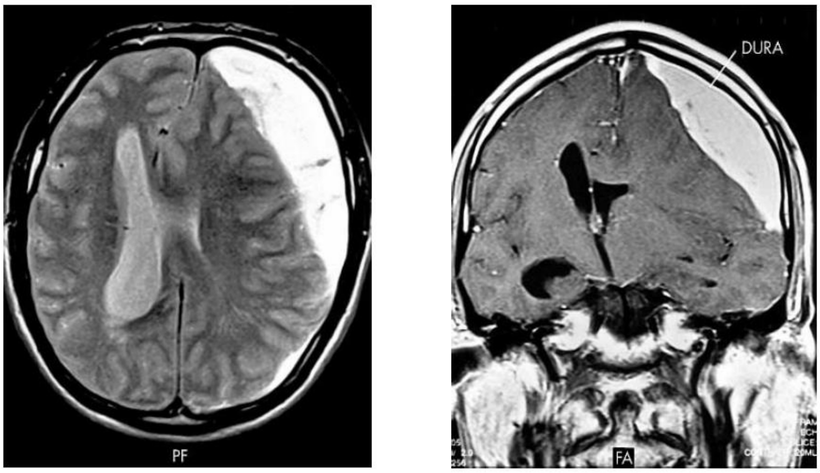

Figure 5. A magnetic resonance imaging scan of the head of a professional snowboarder. The scan revealed an enormous left sided subdural haematoma with a major midline shift and compression of the left lateral ventricle and hemisphere. From Rajan and Zellweger (2004). Reproduced with permission from BMJ Publishing Group Ltd. 29.09.17.

Literature search strategy

To obtain relevant background literature for this thesis, in addition to literature concerning head injury mechanisms specifically among skiers and snowboarders, a PubMed search was performed using the following search terms:

"(craniocerebral trauma[MeSH] OR "head impact*" OR "head injur*) AND (ski* OR snowboard*) AND (hasabstract[text] AND English[lang])"

A broad search was used to obtain literature concerning both epidemiology, aetiology or injury mechanisms (Figure 3). Only articles in English, with an abstract were included. The search revealed 210 papers (Figure 3). Only papers concerning an adult or adolescent population (adolescent age 13 to 18 years, adult age 19+ years) were included, as this is the age group of FIS WC athletes. Papers specifically concerning paediatric subjects (<13) were therefore excluded.

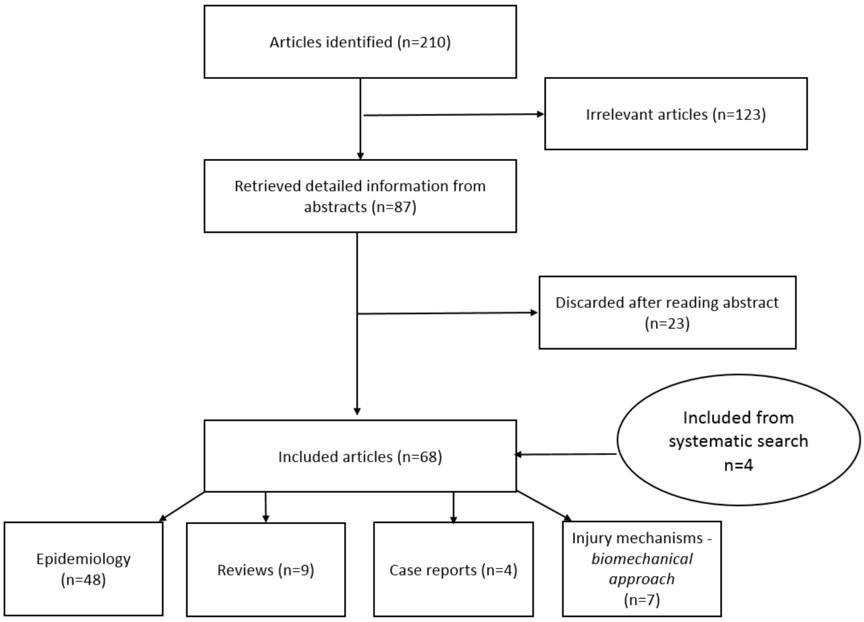

Figure 3. *Flow chart showing the literature selection process.*

After reading the titles, 123 papers were removed, and 87 papers were selected for further reading. After reading the abstracts, 23 papers were removed, because they were not relevant. The remaining 68 papers were classified as epidemiology (n= 48), review papers/metaanalyses (n=9), and injury mechanisms (biomechanical approach) n=3. While most of the epidemiological papers concerned head injury rates, some used an epidemilogical approach to describe injury mechanisms. To further search for articles utilising a biomechanical approach to describe head injury mechanisms, a hand search was performed, and literature lists of the existing studies were examined. This revealed an additional 4 relevant papers, of which 3 came from the *Journal of ASTM International*, which is not indexed on PubMed. One paper was obtained on Google Scholar. In total therefore, 7 papers describing head injury mechanisms from a biomechanical perspective were obtained (Figure 3).

Relevant literature from this literature search regarding head injury mechanisms based on epidemiological literature is presented in Table 1 (p. 20), and the seven obtained studies describing head injury mechanisms based on a biomechanical approach are presented in Table 2 (p. 22).

Epidemiology of head injuries in skiing and snowboarding

Recreational skiing and snowboarding

Head injury prevalence and incidence rates vary among studies; however, concussions and mild Traumatic Brain Injuries (TBI) are more common than severe head injuries in recreational skiing and snowboarding (Sharma et al., 2015, Levy et al., 2002). Nevertheless, while uncommon, TBI is the leading cause of death and catastrophic injury (Ackery et al., 2007). Particularly, young male snowboarders have been found to be especially at risk of death from head injury (Ackery et al., 2007). Although fatal head injuries are uncommon on ski slopes, head injury was the primary cause of death in 46.4% of traumatic deaths among Austrian recreational skiers (Ruedl et al., 2011). Of 1076 head injuries suffered by recreational Japanese skiers and snowboarders, there were 5 fatalities (0, 46%) during a 5-year period (1994-99) (Fukuda et al., 2001). In the United States 87.5% of all skiing and snowboarding deaths were due to head injuries (Levy et al., 2002). However, most of the head injuries were mild TBIs with Glascow Coma Scale scores of 13-15 (81%), and 69% of head injuries were diagnosed as concussions (Levy et al., 2002).

de Roulet et al. (2017) investigated the US National Trauma Data Bank for the period 2007 to 2014 for skiing and snowboarding hospital admissions with major head trauma (Injury Severity Score >15) after falls from skiing and snowboarding (de Roulet et al., 2017). Severe TBI was common for both sports (56.8% of skiers vs. 46.6% of snowboarders) (de Roulet et al., 2017). Sharma et al. (2015) reviewed the National Electronic Injury Surveillance System to acquire data from 7 extreme sports (2000-2011) to investigate the prevalence of head and neck injuries in the USA (Sharma et al., 2015). The 4 sports with the highest total proportion of head and neck injuries were skateboarding, snowboarding, skiing, and motocross (Sharma et al., 2015). Of the snowboarding and skiing head injuries, concussions accounted for 43.9% and 41.9 %, and skull fractures 0.4% and 0.8%, respectively (Sharma et al., 2015).

Concussions have been reported to represent 9.6% of all injuries in skiers and 14.7% in snowboarders (Bridges et al., 2003). Hentschel et al. (2001) compared skiers and snowboarders and found that both had similar rates of head injury (0.005 and 0.004 per 1000 participants, respectively). However, skiers had a greater proportion of concussions (60% vs 21%) and snowboarders had a higher proportion of severe brain injuries (29% vs 15%) (Hentschel et al., 2001).

Epidemiology at the FIS World Cup level

A few epidemiological studies based on the FIS Injury Surveillance System (FIS ISS) have previously reported head injury incidence at the WC level. In WC snowboarding, the head/face (13.2%) was the third most commonly injured body part, following knee and shoulder/clavicle injuries (Major et al., 2014). The risk of head injury was significantly higher in snowboard cross and halfpipe compared to parallell slalom (Major et al., 2014). During six seasons (2006-2012) of WC alpine skiing, head injuries accounted for 10% of all injuries (Bere et al., 2014b), whereas during three seasons (2006-2009) of WC freestyle skiing, head injuries represented 13% of all injuries (Florenes et al., 2010). However, no detailed analysis of head injuries, including investigation into any sex differences, the severity and the types of injuries in the different alpine, freestyle and snowboarding disciplines at the FIS WC level has previously been conducted. Therefore, this was the aim of *Paper I*.

Causes of head injuries in skiing and snowboarding

Risk factors for head injuries in recreational skiers and snowboarders

Epidemiological studies at the recreational level suggest that age, sex and skill level, as well as the injury event location, may be potential risk factors for TBIs in skiers and snowboarders, although there is some discrepancy in the literature.

A retrospective cohort study from 2002 to 2004, identified terrain park use as a risk factor for head injury in skiers and snowboarders, regardless of helmet use (Greve et al., 2009). Carus (2014) performed an exploratory factor analysis among recreational freestyle skiers and snowboarders using terrain parks, to identify factors that can potentially influence the occurrence of accidents in terrain parks. According to the perceptions of the users, the proposed causes of accident occurrence were mainly related to the design of the features within the terrain parks, specifically the height of aerials, width, length and shape of jibs, and launch and landing angles (Carus, 2014).

In a case control study and a later follow-up study, Sulheim et al. (2006 and 2017) evaluated the odds of sustaining a head injury in skiers and snowboarders, in relation to the potential candidate risk factors of age, sex, nationality, skill level, equipment used, ski school attendance and rented or own equipment in 2002, 2010 and 2011(Sulheim et al., 2017, Sulheim et al., 2006). They reported from the univariate analysis of each of the candidate risk factors that there was a continuing gender difference with favourable odds for females (OR: 0.70 in 2002, 95% CI 0.58 to 0.85, $p<0.001$; OR: 0.82 in 2010, 95% CI 0.68 to 0.98, $p=0.03$; OR: 0.80 in 2011, 95% CI 0.66 to 0.98, $p=0.03$). Experienced skiers and snowboarders had greater odds of being head injured in 2002 (OR: 1.43, 95% CI 1.18 to 1.72, $p<0.001$), 2010 (OR: 1.22, 95% CI 1.03 to 1.47, $p=0.03$) and 2011 (OR: 1.25, 95% CI 1.02 to 1.52, $p=0.03$). A greater proportion of injuries occurred in terrain parks in 2010 ($p<0.001$ vs 2002) and 2011 ($p<0.001$ vs 2002). There was a higher proportion of potentially severe head injuries in injured older skiers and snowboarders (>13 years) compared to younger (OR: 1.57 in 2002, 95% CI 1.01 to 0.2.45, $p=0.04$; OR: 1.77 in 2010, 95% CI 1.27 to 2.46, $p<0.001$; OR: 1.20 in 2011, 95% CI 0.97 to 1.64, $p=0.32$). Good and expert skiers and snowboarders consistently had worse odds for severe head injury (OR: 1.38 in 2002, 95% CI 0.1.07 to 0.1.79, $p<0.01$); in 2010: 1.25, 95% CI 1.01 to 1.54, $p<0.05$; (OR: 1.66 in 2011, 95% CI 1.09 to 2.56. $p=0.01$)(Sulheim et al., 2017).

In the United States, skiers and snowboarders under the age of 35 were 3 times more likely to sustain a head injury than older participants, and male skiers and snowboarders were 2.2 times more likely than females to sustain a head injury (Levy et al., 2002). Fukuda et al. (2001) conducted a prospective study of head injuries in skiers and snowboarders in Japan between 1994 and 1999 and reported that the average age of head injured snowboarders was 3.6 years younger than that of skiers (22.2 and 25.8, respectively). Male snowboarders were most at risk of head injury (63%) while in skiers 51% of injuries were in males (Fukuda et al., 2001). Nakaguchi et al. (1999) reported the results of a prospective study on head injury in skiing and snowboarding in Japan (1995–1997). They reported that beginner snowboarders were more likely to suffer head injuries and had a higher incidence of severe head injuries than beginner skiers (60 of 142 vs. 48 of 154, $p = 0.022$) (Nakaguchi et al., 1999). Based on ski patrol injury reports, ski days of high school outings in British Columbia, Canada were associated with a 25% higher likelihood of injury than outings involving participants aged 18 or older (Macnab and Cadman, 1996).

Bridges et al (2003) conducted a study of snow sport injuries in eastern Canada. Most concussions occurred after 2–5 hours of activity in intermediate participants and in those who had not had a lesson, as well as those who were skiing recreationally rather than competing. The risk of sustaining a concussion on ungroomed and rough snow was 2.5 times greater than for soft snow. Male participants were more likely to sustain a head injury than female participants (Bridges et al., 2003).

No studies have investigated risk factors for head injuries specifically in WC skiers and snowboarders. Spörri et al. (2012) performed a qualitative study to explore perceived key risk factors for severe injuries among expert stakeholders in the alpine WC, and identified five key categories: system ski, binding, plate and boot; changing snow conditions; physical aspects of the athletes; speed and course setting aspects and speed in general (Sporri et al., 2012). Although this study was not designed for head injuries specifically, but severe injuries in general, some or all of these key risk factors may also be relevant for head injuries. However, further investigation into the risk of head injuries specifically, at the alpine, freestyle and snowboarding WC level is needed.

Head Injury mechanisms

The potential for concussion is related to the number of opportunities within a sport for events that cause a direct blow to the head, face and neck, or for an impulsive force transmitted to the head from elsewhere on the body (Patton, 2016, Meaney and Smith, 2011, McCrory et al., 2017). For example, a snowboarder who is sleep deprived, is feeling unwell and is slightly dehydrated, is predisposed to injury (internal risk factors). If she in addition does not have an optimally prepared board for the snow conditions, while riding on a course with high wind and low visibility (external risk factors), she will potentially be susceptible for head injury. However, for a head injury to occur she must fall and receive an impact to her head, or receive an impulse loading to the head. The crash where she receives the head impact is the inciting event, or injury mechanism. Therefore, to understand the complex causes of head injuries in skiers and snowboarders, one essential component is to describe the head injury mechanism (inciting event) in as much detail as possible.

Detailed brain injury mechanisms vs gross head impact injury mechanisms

In skiing and snowboarding head injury situations, the most common injury mechanism is a direct impact loading to the head, where the head impacts a surface such as the snow, a foreign object such as a tree or another person (Bailly et al., 2017, Greve et al., 2009, Siu et al., 2004). This impact loading will cause kinetic energy to be applied to the cranium, so that both acceleration-deceleration and rotational mechanisms occur (Bailes and Cantu, 2001). The direct head impact loading is the gross head injury mechanism that is identifiable from visual inspection alone. Therefore, to describe injury mechanisms in this thesis, only a description of the injury mechanism causing the direct impact loading to the head will be given. From visual inspection of broadcast video, only an account of the gross (full body) biomechanics of the head impact injury situation is possible. We cannot describe the detailed intracranial brain injury mechanisms or the detailed brain response to impact loading, from visual inspection of broadcast video, i.e. we cannot describe what happens intracranially from visual analysis of video. The injuries will be referred to in *Papers II, III and IV* as "head impact injuries" to clarify that we are analysing head injuries caused by impact loading to the head (that we can identify on video). In *Papers II, III and IV*, we will also use the term "gross head impact injury mechanism" to clarify that we are describing full body injury mechanisms. In *Papers III and IV* we will use the term "gross head impact biomechanics" because we are describing the gross head impact kinematics, and not the detailed intracranial brain injury mechanisms. This means that from our two dimensional motion analysis *(Papers III and IV)*, we gain information about the whole body biomechanics, such as head velocity, but not detailed biomechanical information about e.g brain tissue strain. While the focus of this thesis therefore, is to describe gross head impact injury mechanisms and gross head impact biomechanics, to understand more about the causes of head injuries, it is important to have insight into how the gross head impact injury mechanisms and gross head impact biomechanics could influence the detailed brain injury mechanisms.

Detailed mechanisms of brain injuries

Acceleration-deceleration injury, also considered translational (linear) impact, usually results when the subject's body and head are traveling at a particular speed and strike a solid object. Similarly, a head at rest may be struck by a moving object (Bailes and Cantu, 2001). Newton's second law of motion states that a force (F) is equal to the mass (m) of an object multiplied by the acceleration (a) of that object $(\overrightarrow{F} = m\overrightarrow{a})$. Exemplified by American football, this means that as the magnitude of the force from the striking player increases, the head acceleration of the struck player must increase as the mass of the head is constant (Broglio et al., 2012). The resultant injury causes linear, tensile, and compressive strains that may disrupt the cerebral anatomy and cytoarchitecture (Bailes and Cantu, 2001).

Cantu (1996) described three types of stress that can be generated by an acceleration force to the head: 1) compressive, 2) tensile (or negative pressure), 3) shearing (a force applied parallel to a surface) (Cantu, 1996). Uniform compressive and tensile forces are relatively well tolerated by neural tissue, but shearing forces are extremly poorly tolerated (Cantu, 1996).

According to McIntosh et al. (2011) a pure radial (linear) impact will cause linear acceleration of the head while a pure tangential impact around the head's centre of gravity will cause rotational acceleration of the head (Figure 6). However, in a real life sports setting, it is more likely that an oblique impact will occur that gives rise to both linear and rotational head acceleration (McIntosh et al., 2011). Pure radial impacts are rare and would mainly cause skull fractures and injuries secondary to those (McIntosh et al., 2011). It is believed that linear acceleration is more directly involved in the compression of cerebral tissue following impact, whereas rotational acceleration is more related to the shearing of cerebral neurons (Broglio et al., 2012, Ommaya and Gennarelli, 1974, Adams et al., 1989, Gennarelli, 1993). In agreement, Kleiven (2013) reported from finite element modelling of head injury risk, that skull fractures as opposed to TBIs were more likely to occur as a result of linear acceleration, and that concussions, diffuse axonal injury, contusions, subdural hematoma and intra-cerebral hematomas may be more likely induced by rotational kinematics (Kleiven, 2013). In line with this, Barth et al. (2001) dicussed that multiple vectors of acceleration and deceleration in response to forces applied to the brain likely account for the greatest axonal injuries in mild TBI, and that these likely lead to the greatest impairments in neurobehavioral outcome (Barth et al., 2001).

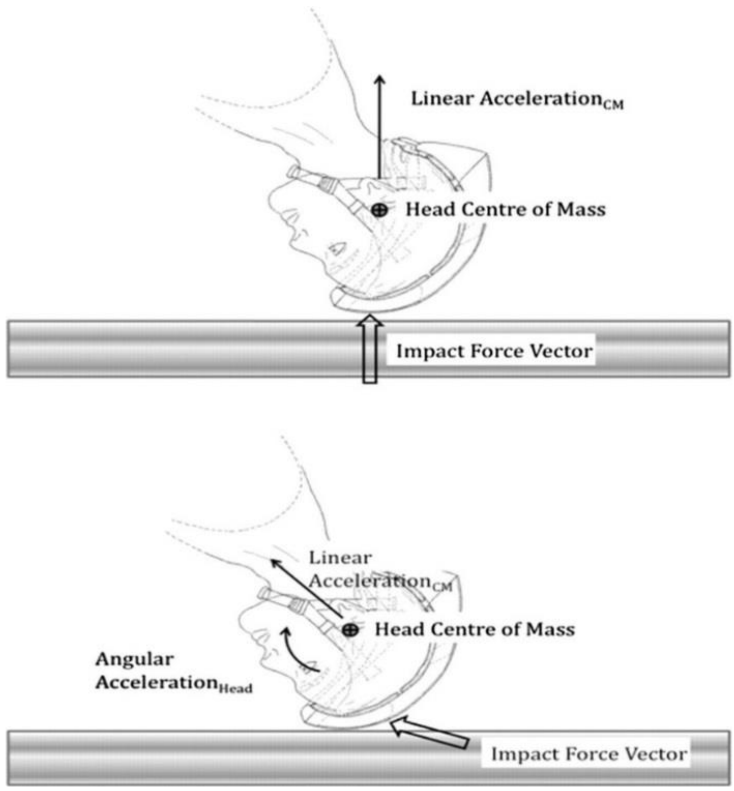

Figure 6. *Schematic diagram of head impact. Radial impact (top) with linear head acceleration outcome and oblique impact (lower) with linear and angular head acceleration outcome. From McIntosh et al. (2011), Permission to reproduce image obtained from BMJ pulishing group Ltd: 07.07.2017*

Research approaches to describe head injury mechanisms in skiing and snowboarding

Krosshaug et al. (2005) presented a number of different methodological approaches to describe the inciting event for sports injuries. These include interviews of injured athletes, analysis of video recordings of actual injuries, clinical studies, in vivo studies, cadaver studies, mathematical modelling and simulation of injury situations, and measurement/estimation from "close to injury" situations (Krosshaug et al., 2005). However, according to Krosshaug et al. (2005), for most injury types, one research approach alone will not be sufficient to describe all aspects of the injury situation, and it is therefore necessary to combine a number of different research approaches to describe the mechanisms fully. For example, relevant combinations of research approaches that could provide a broader understanding could be combining athlete interviews, video analysis, and clinical studies, or combining video analysis and cadaver/dummy/mathematical simulation studies (Krosshaug et al., 2005).

Literature investigating head injury mechanisms in skiing and snowboarding has primarily used retrospective athlete interviews and questionnaires to describe gross injury mechanisms (Table 1). However, a few studies have either used three dimensional video analysis of actual injuries (Yamazaki et al., 2015), real time in vivo measurements (utilising helmet mounted accelerometers)(Mecham et al., 1999, Dickson et al., 2016), mathematical modelling (Bailly et al., 2016) or laboratory reconstructions with anthropomorphic test devices to describe the injury mechanisms in more detail (Dressler et al., 2012, Richards et al., 2008, Scher et al., 2006) (Table 2).

Retrospective interviews, hospital records and accident reports

One of the most commonly used approaches in studying injury mechanisms is the description of the injury as reported by the athlete, coach, medical personnel or others who witnessed the accident(Table 1). Using this approach, it may be possible to describe the inciting event preceding the injury and the injury mechanism at the time of injury (Krosshaug et al., 2005). Advantages of this approach are that it is relatively easy and inexpensive to obtain data from a large number of injured athletes (Krosshaug et al., 2005). Also, questionnaire data can potentially provide an accurate description of the mechanisms related to the skiing/snowboarding situation and athlete/opponent behaviour (Krosshaug et al., 2005).

Bailly et al.(2017) conducted a large hospital based survey, where they asked head injured skiers and snowboarders to identify the head inury mechanisms from presented sketches (Table 1). They reported that falls, collision between users and jumps were the most common injury mechanisms. However, collisions with obstacles caused the most serious cases of TBI`s (Bailly et al., 2017).

Xiang & Stallones (2003) reported that the greatest number of deaths associated with recreational alpine skiing occurred between 10:00 a.m. and 2:00 p.m, and 35.2% of cases were pronounced dead at the scene (Table 1). Among the 174 deaths associated with alpine skiing, 74 cases died of traumatic head injuries, and 59 died of other blunt traumatic injuries. A majority (n=113, 64.9%) of cases involved collisions between skiers and stationary objects or other skiers: 91 victims hit trees, 7 hit other skiers, 4 hit posts, and 11 hit other objects (Xiang and Stallones, 2003).

Koyama et al. (2011) reported that in recreational snowboarders, head injuries mostly occurred after falls on slopes in beginners and during jumping in intermediate and expert riders (Table 1). The impact point on the head was predominantly occipital in both beginners and intermediate/expert riders, but the intermediate/expert group had a significantly higher frequency of trauma to the frontal region. The ratio of neurologic abnormalities was significantly higher among intermediate/expert riders compared to beginners. However, the ratio of surgical cases was significantly higher among beginners (n = 10,1.04%) than in intermediate/experts (n = 5, 0.36%). More acute subdural hematomas were seen in beginners, but intermediate/expert riders had more fractures, contusions, and acute epidural hematomas (Koyama et al., 2011).

In a 10-year retrospective review of the Alberta Trauma Registry, McBeth et al. (2009) identified a total of 196 patients (56.6% skiers, 43.4% snowboarders) as having major traumatic injuries (Injury Severity Score, ≥12)(Table 1). Fortythree patients required intensive care unit support. The majority of injuries were related to falls and collisions with natural objects. Head injuries were most common, followed by chest, spinal, and extremity trauma (McBeth et al., 2009).

Table 1. Relevant literature describing gross (full body) head injury mechanisms in recreational skiing and snowboarding, based on surveys, interviews, hospital records etc.

Reference	**Study period**	**Population, cases**	**Sport**	**Type of head injury (Definition used)**	**Approach**	**Injury mechanism(s)**
Bailly et al. (2017), France	2013-2015	Head injuries: 221♂ 145♀	Recreational skiing and snowboarding	TBI, based on GCS score	Hospital survey combined with sketches to describe crash and impact locations	Falls (54%), collision between users (18%), jumps (15%). Collision with obstacle (13%) caused most serious TBI. ***Skiers***: Falling head first while skiing (28%), Falling sideways (catching the ski edge) (19%). Mainly forward falls, impacts to frontal (57%) and facial (41%) areas. ***Snowboarders***: Falling forward (38%), falling backward (41%). Forward falls: impacts to frontal (47%) and facial (47%) areas. Backward falls: impacts to occipital (56%) and facial (38%) areas.
Russel et al. (2013), Canada	2008-2010	333	Recreational snowboarding	Head injury (location) Concussion (type)	Retrospective, case series, ski patrol/ hospital records	Using aerial features (jumping-falling)
Ruedl et al. (2011), Austria	2005-2010	108 head injuries: (101♂,7♀) deaths n= 45	Recreational alpine skiers and snowboarders	Head injury- traumatic death	Retrospective analysis Data collected by ski patrol	Fall during skiing (41%), collision with other skier (19%), impact with solid object (35%), avalanche on slope (4%)
Koyama et al. (2011), Japan	1999-2008	2367 head injuries (1513♂,854♀) Beginners: 959 Intermediate/ expert: 1408	Recreational snowboarders	No neurological findings, amnesia, loss of consciousness, fractures, SAH, SDH, EDH, contusion	Descriptive epidemiological study, questionnaire data	Beginners: Location- gentle slopes (37%) and intermediate slopes (33%), falls (67%) Intermediate/experts: Location- jumps (48%), colliding with obstacles (3%)
Brooks et al. (2010), USA	2000-2005	14781(8985♂, 5774♀)	Recreational alpine skiers and snowboarders	Head injury (location) Concussion (type)	Cross sectional, data obtained from ski patrol reports	High falls in terrain parks (elevated jump, cliff). Terrain park use = more head injuries/concussions vs. traditional slopes
Greve et al. (2009), USA	2002-2004	1013 injury cases, (722♂, 280♀)	Recreational alpine skiers and snowboarders	Head injury by ICD-9 codes, from clavicle up, GCS score, loss of consciousness.	Retrospective cohort Review of emergency department medical records	Hitting head on snow (74%), collision with other skiers (10%), collision with fixed objects (13%), terrain park use vs. regular slope (χ^2 :5.800, $p<0.05$)

Reference	Study period	Population, cases	Sport	Type of head injury (Definition used)	Approach	Injury mechanism(s)
McBeth et al. (2009), Canada	1996-2006	196 patients, (160♂,36♀)	Recreational skiers and snowboarders	Head injury, brain injury, and injuries to other body parts, classified by GCS, AIS or ISS	Retrospective review, hospital records	Falling (46%), while riding (44%), collision (33%), colliding with tree (21%), Jumping (20%), colliding with another person (6%), hitting rock (3%)
Siu et al. (2004), Australia	1994-2002	66♂,25♀, 25 head injuries	Recreational alpine skiers and snowboarders	Skull fracture, concussion, contusion, intracranial haemorrhage, SDH, EDH, SAH, diffuse brain injury	Retrospective, computerised search of hospital database	Collision (44%) (With stationary object, tree, other skier/snowboarder), fall (40%), jump (8%), others (8%). Direction of fall: forward (12%), backward (28%), sideways (24%), other (36%)
Xiang & Stallones (2003), USA	1980-2001	231♂,43♀, 90 deaths from head trauma	Recreational alpine skiers and cross country skiers	Traumatic head injuries, death	Retrospective, descriptive analysis based on death certificates	Collisions: with tree (52%), with other skiers (4%), other objects (6%), a post (2%). Falls (6%) Geneal skiing accidents (16%) Avalanche (5%)
Nakaguchi & Tsutsumi (2002), Japan	1995-2001	38 hospital admissions (8♀, 30♂)	Recreational snowboarders	Coup, contrecoup or shear injuries	Retrospective, hospital records	Falling backwards (68%), occipital impact (66%), gentle or moderate ski slope (76%), inertial injury (76%), "Opposite edge mechanisms". Acute SDH frequently occurred after a fall on slope, backwards falls, in occipital impacts.
Fedreiuk et al. (2002), USA	1992-1999	132 patients (106♂,26♀)	Recreational snowboarders, alpine skiers and sledders	Head injuries and injuries to other body parts based on ISS	Retrospective, state trauma registry	Snowboarders: significanltly more falls from heights (29%) vs skiers/sledders (OR = 4.8; 95% CI, 1.6 to 13.7)
Fukuda et al. (2001), Japan	1994-1999	1076 hospitalised patients (629♂,447♀)	Recreational alpine skiers and snowboarders	Many diagnoses, based on criteria of neurologic findings or organic lesions	Prospective analysis, hospital records	Falls, jumping, collisions (with other skiers/snowboarders, trees, lift towers, edge of ski/snowboard). Middle or easy slopes.

Abbreviations: TBI: traumatic brain injury, SDH: subdural haemorrhage, EDH: epidural haemorrhage, SAH: subarachnoid haemorrhage, GCS: Glasgow Coma Scale, ICD-9: International Classification of Diseases-9, AIS: Abbreviated injury scale, ISS: Injury severity score

Table 2. Relevant studies using different biomechanical methods to give a detailed description of head impact situations in skiers and snowboarders

Reference	Sport situation	Approach	Injury mechanism	Head impact kinematics/kinetics
Bailly et al. (2016), France	Snowboarding	***Mathemetical modelling*** Human body model created with MADYMO software	Snowboard back edge catch, impact to rear of head	Mean normal head impact speed (28±6 km/h) Mean tangential impact speed, (13.8±7 km/h). In 97% of simulated impacts peak head acceleration below 300 g,
Yamazaki et al. (2015), Norway/Japan	World Cup alpine skiing	***3D video analysis*** Retrospective case report, 3D Model Based Image Matching Technique	Falling laterally after a jump, striking head onto snow.	Downward velocity component 8 m/s, post-impact upwards velocity 3 m/s, velocity parallel to slope surface reduced from 33-22 m/s, frontal plane angular velocity changed from 80 rad/s left tilt before to 20 rad/s right tilt immediately after impact.
Dickson et al. (2015), Australia	School-aged students, skiing/snowboarding	***In vivo- biomechanical wearables*** Head Impact Telemetry System (accelerometres) fitted helmets and GPS devices	Head accelerations in general while skiing/snowboarding	970 head accelerations (46.3% skiers, 53.7% snowboarders), 6.0 per session (4.0 per skiing session, 9.8 per snowboarding session) 61% of linear accelerations <20 g, 9% >40 g 2 recorded accelerations were expected to result in a concussion (>98 g)
Dressler et al. (2012), USA	Skiing/snowboarding	***Dummy study*** Instrumented 50th percentile male Hybrid III anthropomorphic test device (head and neck assembly)	Head first impacts onto soft and hard snow, helmeted and unhelmeted, in custom built drop carriage.	*Soft snow*: peak resultant head accelerations 30-42g without helmet, 28-38g with a helmet *Hard snow*: peak head accelerations 138-165g without helmet, 79-98g with helmet. Helmet reduced head accelerations by 32-48% on hard snow. *Neck loads, soft snow*: peak axial neck loads 5562-6948N without helmet, 4287-5991N with helmet *Neck loads, hard snow*: 9511-10748N without helmet, 9389-9864N with helmet.
Richards et al. (2008), USA	Snowboarding	***Dummy study*** Instrumented 50th percentile male Hybrid III anthropomorphic test device	Snowboard back edge catch, impact to rear of head	Mean head velocity normal to slope increased from ≈ zero at fall initiation to 37.1 km/h during the fall, 29.1 km/h at snow contact. Resultant head velocity peak 54.3 km/h 38.2 km/h at snow contact

Reference	Reconstructed sport situation	Approach	Injury mechanism	Head impact kinematics/kinetics
Scher et al. (2006), USA	Snowboarding	***Dummy study*** Instrumented 50th percentile male Hybrid III anthropomorphic test device	Snowboard back edge catch, impact to rear of head on soft snow and hard snow, helmeted and unhelmeted	Soft snow, peak head accelerations: helmeted 83±23g, unhelmeted 74±39g Hard snow, average maximum head accelerations: helmeted 162g±34g, unhelmeted 391g±105g
Mecham et al. (1999), USA	Elite Freestyle aerials	***In vivo- biomechanical wearables*** Field study, video & collection of head impact data (helmet mounted tri-axial accelerometer)	Slapback episodes (♂♀16%), impacts to rear of head.	Max. head acceleration magnitude range 27-92g, impact durations 12-96µsec, Head Impact Criterion range: 21-159. Probability of slapbacks increased with increasing jump height.

At the recreational level, injury characteristics may be related to the injury location in terrain parks and types of manoeuvres performed there, rather than the type of activity (skiing or snowboarding)(Table 1) (Brooks et al., 2010). However, snowboarders had significantly more falls from heights compared skiers (Federiuk et al., 2002). Jumping and using aerial features in terrain parks were found to increase head injury risk compared to skiing/riding on a traditional slope (Russell et al., 2013, Greve et al., 2009, Brooks et al., 2010). The incidence of head injuries was higher on aerial features in the terrain park compared to on non-aerial features (15.3% (95% CI 11.1 to 20.5) vs. 8.9% (4.8 to 15.5)) and the same was found for concussions (aerial 11.4% (8.0 to 16.2) vs. non-aerial 7.3% (3.7 to 13.4)) (Russell et al., 2013). Both skiers and snowboarders were more likely to suffer injuries to the head (15%) and concussions (14.6%) in a terrain park compared to on a traditional ski slope (8,9% and 6,5%, respectively) (Brooks et al., 2010).

Fukuda et al. (2001) (Table 1) reported that during a 5-year study into the comparison of head injuries in snowboarders and skiers, the injury patterns were either falling on a slope, jumping, and one fall on concrete (Fukuda et al., 2001). For all head injuries, falls were the most frequent cause of injury in both skiers and snowboarders, while crashing after jumping was a more frequent cause of injury in snowboarders (30%) compared to skiers (2.5%) (Fukuda et al., 2001).

Nakaguchi and Tsutsumi (2002) (Table 1) reported that the majority of severe head injuries associated with recreational snowboarding, occurred after simple falls on the slope.(Nakaguchi and Tsutsumi, 2002) Falling backwards leading to occipital impact was the primary injury mechanism, with inertial forces being most injury producing. The back-edge catch mechanism, where a snowboarder caught the snow with the down-valley edge and fell backwards, was the main gross injury mechanism (Nakaguchi and Tsutsumi, 2002).

Limitations of these methods include the fact that there might be a lack of precise definitions used when reporting data (Krosshaug et al., 2005). For example, different definitions of head injuries are used, such as concussion, TBI, mTBI, fractures, neurologic injuries, death etc. (table 1). This reflects the fact that different studies have different aims, i.e. recording all head injuries, recording concussions specifically or recording fatalities. It is also apparent that studies use different definitions of concussion. Also, as expected, the terms mTBI and concussion were used interchangeably in some cases.

The categorisation of injury mechanisms into predefined descriptions may result in incomplete or incorrect information (Krosshaug et al., 2005). An approach to combat this problem could be to ask the interviewee to describe the injury mechanism in his/her own words in an open ended question, and later attempt to categorise the answers. This was done by Brandenburg and Archer (2005), who sent out a survey asking bull riders to describe each incident of head injury they had sustained during their career. This resulted in 84 injury situations being described, which were later categorised by the authors into 6 injury mechanism categories (Brandenburg and Archer, 2005). A challenge, however, in asking the injured athlete to describe the injury mechanism, is related to the fact that in some cases, head injuries are associated with a loss of consciousness. Athletes may therefore have trouble recollecting exactly what happened at the time of injury, and may be influenced by what he/she was told by others witnessing the event (recall bias). Recall bias is a systematic error caused by differences in the accuracy or completeness of the recollections retrieved by study participants regarding events or experiences from the past (Peat et al., 2002). Also in other cases, recall bias is a challenge with retrospective interviews as the athletes recollection of what happened may change with time (Peat et al., 2002). However, many accounts of injury mechanisms achieved from e.g. medical reports used broad categories of injury mechanisms, such as “fall”, “collision” or “contact with a foreign object”. One can presume that the athlete or witnesses could be able to accurately describe these types of mechanisms.

Video analysis

As discussed above, approaches that determine the mechanisms of injury by patient self-report or eyewitness accounts can suffer sigificant limitations due to recall bias or observation and recording errors when attempting to describe specific at risk scenarios and injury mechanisms in sport (Krosshaug et al., 2005). Video analysis can overcome these limitations by providing researchers with an opportunity to record, analyse, and describe injury mechanisms and specific characteristics of the sport (Quarrie and Hopkins, 2008).

However, one limitation of all video analysis approaches is the quality of the video recording, for example the image quality, the resolution of the athlete of interest and the number of views available (Krosshaug and Bahr, 2005, Krosshaug et al., 2005). Another challenge might be to determine the exact timepoint of injury. In snowboarding and skiing head injury cases, if one considers that most head injuries are impact injuries, it should nevertheless be feasible for a group of experts to determine the moment of impact(s) and to provide a gross description of the injury mechanism. There are three types of video analysis used in reserach: simple visual inspection, two dimentional (2D) video analysis, and three dimensional (3D) video analysis. These methods will be discussed in the following sections.

Simple visual inspection

Systematic visual inspection of injury videos has been a very useful approach to describe anterior cruciate ligament injury mechanisms, and events leading to injury situations in WC alpine skiers (Bere et al., 2014a, Bere et al., 2011a, Bere et al., 2011b). From these analyses, Bere et al. (2014a) reported that 96% of injuries to the head and upper body in WC alpine skiers resulted from crashes. However, there has been no systematic video analysis of head and face injuries at the recreational level, or in WC alpine and freestyle skiing and snowboarding. Therefore, the main objective of *Paper II* was to conduct a systematic video analysis of head and face injuries among WC alpine and freestyle skiers and snowboarders, to describe their gross injury mechanisms.

2D video analysis

While visual analysis can provide valuable information about the events leading to injury situations and gross head injury mechanisms, quantitative motion analysis can provide more detail, such as estimates of the kinematics of head impact injuries (Pellman et al., 2003b). Kinematic analysis techniques typically consist of cinematography and motion tracking systems offering 2D or 3D information on body segment translation, rotation, velocity and to a limited extent, acceleration (Shewchenko et al., 2005). 3D motion analysis is considered the "gold standard" for evaluating kinematic variables; however, its use is limited by temporal and financial restraints (Maykut et al., 2015). 2D motion analysis requires movements to be in a pre-selected movement plane, and therefore has acceptable results for essentially planar movements (Schurr et al., 2017).

In previous head injury research, 2D motion analysis has been used alone, or combined with further dummy studies or mathematical modelling. McIntosh et al. (2000) examined videos of head impacts that resulted in concussions in rugby and Australian rules football, to obtain 2D estimates of closing speed and head impact energy. The mean change in velocity of the head was 4 m/s, and concussion was estimated to occur when the impact force generated was 50-60 J, the equivalent to 200g. There was however, a 10% error associated with the 2D analysis (McIntosh et al., 2000).

As exemplified by McIntosh et al. (2000), the 2D motion analysis itself can give useful estimates of head impact kinematics, although there is a certain amount of expected error associated with this type of motion analysis. However, 2D motion analysis should be a reasonable approach to use for quantitative video analysis of head and face injuries among WC alpine and freestyle skiers and snowboarders. This however, requires that the videos meet specific selection criteria, mainly relating to the plane of movement.

3D video analysis

-Model Based Image Matching

As many injury situations cannot be realistically reconstructed in the laboratory, particular interest lies in utilizing video data optimally and therefore, a new method of using video analysis combined with Model-Based Image Matching (MBIM) techniques was developed by Krosshaug & Bahr (2005). Importantly, to obtain valid analyses of head impact kinematics, information from real injury situations is crucial (Patton, 2016).

One previous study has used the MBIM technique to analyse one case of a severe TBI in an alpine skier (Yamazaki et al., 2015). Yamazaki et al. (2015) reported that the mechanism of injury occurred at take-off from a jump, where the skier was observed to rotate about his longitudinal axis (Table 2). As a result of this rotation he landed with his skis out of line with his body's velocity. The skier lost control at touch down, fell laterally and struck his head. Immediately before head impact, the downward velocity component normal to the surface was estimated to be 8 m/s. After impact, the upwards velocity was 3 m/s, whereas the velocity parallel to the slope surface was reduced from 33 m/s to 22 m/s. The frontal plane angular velocity of the head changed from 80 rad/s left tilt immediately before impact to 20 rad/s right tilt immediately after impact (Yamazaki et al., 2015).

Yamazaki et al. (2015) exemplified that if it is possible to attain high quality video footage, with a view of the injury from several angles, in addition to measurements of landmarks, and accurate medical information, video analysis combined with a MBIM technique is a good approach to describe injury mechanisms in detail. If it is possible to obtain information from four camera angles, a more precise description of the injury situation is possible compared with utilising a 2D approach. With the MBIM approach therefore, it is possible to obtain information about kinematics in three dimensions, and this is therefore a particularily useful approach in sports where it is difficult to perform laboratory reconstructions with high external validity, such as in skiing and snowboarding (Krosshaug and Bahr, 2005).

Cadaver and dummy studies

Anthropomorphic test devices (ATDs), or dummies, are mechanical surrogates of the human that are primarily used by the automotive industry to evaluate the occupant protection potential of various types of restraint systems in simulated collisions of new vehicle designs (Mertz, 2002). One main area of sports head injury research where dummy studies are used, is to measure resultant linear or angular head acceleration, head injury criterion (HIC), peak head velocity or velocity changes from different reconstructed sporting situations (Fife et al., 2013). Dummies are used in head injury research for obvious reasons, as it would be unethical to perform e.g. helmet or headgear tests, or punch machine tests, as in boxing head injury reserach, on humans (O'Sullivan and Fife, 2016). Dummies, such as Hybrid III ATDs, have good biofidelity, and can be instrumented with, for example, load sensors and accelerometers (Mertz, 1985). The biofidelity of an object relates to its quality of being lifelike in appearance or responses. This means that they mimic relevant human physical characteristics such as size, shape, mass, stiffness, and energy absorption and dissipation, so that their mechanical responses simulate corresponding human responses of trajectory, velocity, acceleration, deformation, and articulation when the dummies are exposed to prescribed simulated collision conditions (Mertz, 2002). However, as dummies are passive, which means that they lack muscles, the types of injuries that can be investigated using this approach are limited (Krosshaug et al., 2005).

In skiing and snowboarding, three studies have reconstructed head impact situations in a laboratory setting with ATDs (Table 2) (Dressler et al., 2012, Scher et al., 2006, Richards et al., 2008).

To investigate if skiing helmets would reduce the likelihood of head injury associated with a snowboarding back edge catch, Scher et al. (2006) used an instrumented 50th percentile male Hybrid III ATD to determine the head accelerations and neck loads associated with a back-edge catch onto the occiput, both with and without wearing a helmet (Table 2). On soft snow, peak head accelerations were not significantly different with a helmet (83±23g) versus without (74±39g). On hard, icy snow, helmeted head contact to the surface produced an average maximum head acceleration of 162 ±34g, while the non-helmeted trials produced a significantly higher average of 391±105g. This meant that on hard, icy snow, using a helmet reduced the probability of skull fracture and severe brain injury from 80% to 20% (Scher et al., 2006).

Using the same test-protocol as Scher et al. (2006), Richards et al. (2008) described the fall kinematics of the ATDs throughout the back-edge catch using 2D motion analysis (Table 2). The mean head velocity normal-to-slope increased from approximately zero at fall initiation to 8.1 m/s at snow contact. Resultant head velocity was 10.6 m/s at snow contact. Richards et al. (2008) discussed that the high impact velocities were the result of the coupled dynamics of the body and the high angular rotation and whipping motion of the head that occurred as a result of the back-edge catch (Richards et al., 2008).

Dressler et al. (2012) assessed the potential for serious neck injury in head-first impacts onto snow surfaces with and without helmets (Table 2). They performed drop tests with a head and neck assembly from a Hybrid III ATD with and without helmets on soft and hard snow. The impact speed was 4.0 ± 0.1 m/s. The helmets provided good head protection in the hard snow impacts, reducing head accelerations by 48%. Head accelerations were low in soft snow impacts both with and without a helmet. Helmets were not an effective countermeasure to high neck loads, although a minor reduction was noted in the soft snow impacts (Dressler et al., 2012).

In laboratory reconstructions with ATDs, the external validity should be assessed by comparing the reconstructed crash sequences with real-life head impacts. We discuss this in detail in *Papers II, III and IV*. In addition, there are several other limitations with surrogate/dummy testing methods. To exemplify, Pellman et al. (2003a, 2003b) studied cases of head injuries from NFL games to estimate the speed of impact from the game videos. From these estimates, the situations were reconstructed in the laboratory using helmeted Hybrid III ATDs to estimate cranial centre of mass acceleration. The laboratory re-enactments only included 31 of 182 cases, and the mathematical derivations were extrapolated from relatively low-speed video capture frequencies. Also, many factors in football game situations cannot be replicated with laboratory tests using crash dummies, and the estimated error using this technique was 15% of the peak values (Pellman et al., 2003b, Pellman et al., 2003a).

In addition, other limitations include that the dummy might not be the same size as the athlete, dummies may not have articulated temporomandibular joints but a fixed jaw, and in situations where helmeted head impacts are reconstructed, the helmet coupling to the dummy might be different than the coupling (fit) of an athlete wearing a helmet (Pellman et al., 2003b, Pellman et al., 2003a). There are also associated measurement errors (Pellman et al., 2003b, Pellman et al., 2003a). In addition, according to Beckwith et al. (2013), three primary limitations exist when trying to relate head kinematics obtained from laboratory impacts to those experienced by athletes who are diagnosed with concussion in sports: 1) sports-related concussion is typically diagnosed by signs of neurological and or neuropsychological dysfunction and self-reported symptomatology, which cannot easily be deduced from surrogates, 2) surrogate tests do not account for the complex system of intrinsic and extrinsic variables (e.g. contact force and direction, player physiology at time of impact, equipment condition, and player anticipation) that influences kinematic response to impact, and 3) single-impact events created in the laboratory may be an insufficient injury model considering impact and/or injury history may modulate an athlete`s tolerance to impact (Beckwith et al., 2013).

In vivo measurements - *Biomechanical wearables*

In an attempt to overcome the above limitations therefore, recent advances in technology have enabled the development of instrumented equipment, which can estimate the head impact kinematics of human subjects in vivo (Patton, 2016). Instrumented (accelerometre fitted) helmets have been used in American football and ice hockey, whilst instrumented headgear and headbands have been used in boxing and soccer (Patton, 2016). Instrumented mouthguards and skin patches have been developed for use in contact and collision sports that do not require wearing helmets or headgear such as soccer, rugby league, rugby union, and Australian football (Patton, 2016).

Two studies have used accelerometer-fitted helmets to investigate head impact magnitudes in skiers and snowboarders (Table 2) (Dickson et al., 2016, Mecham et al., 1999). Mecham et al. (1999) investigated the incidence of head impact and head accelerations during slapback episodes in aerial skiers (Table 2). A slapback episode is contact between the upper back and head with the landing surface, thought to be a common head injury mechanism in freestyle aerials (Figure 7). According to Mecham et al. (1999), during slapback events, athletes experience both direct head impacts and rotational acceleration of the head. The proportion of slapback injuries was 16% for both sexes, with 4 registered concussions, and the probability of slapback injuries increased with increasing jump height. The maximum impact recorded (on the helmet) during a slapback was 92g and the maximum duration of impact was 92μs (Mecham et al., 1999).

Figure 7. *Freestyle aerials, an example of a `slapback´ head impact (from Paper II). Key crash events: A) The athlete is airborne during an inverted jump. B) The athlete has over-rotated the jump, and lands back-weighted. C) Continues to rotate and pitches backward. D) The back of the helmet impacts the snow (impact frame). E) The head and upper body rebound up from the snow. F) The athlete stands up fully.*

Dickson et al. (2015) measured the incidence and severity of pediatric head accelerations by fitting students with instrumented helmets and global positioning system devices during skiing or snowboarding (Table 2). Head accelerations over 10 g were rare, with only three head impacts in total over 40 g. They reported that the head impact speeds were higher than helmet testing standards (Dickson et al., 2016). However, the speeds measured in this study were the actual skiing and snowboarding speeds of the students, not the normal-to-slope head impact velocities. Dickson et al. (2015) reported that the mean maximum speed for all ski/snowboard groups was over 30 km/h (8.3 m/s) and that they were therefore exceeding the impact tests of the helmet standards (ASTM F2040 or EN 1077, testing speeds 5.4 or 6.2 m/s). The authors believed that skiing speed along the slope equals the normal-to-slope head impact velocity.

Instrumented helmets are validated using ATDs (headforms), while both ATDs and rigid body models (discussed below) are validated against cadaveric experiments (Patton et al., 2013). Therefore all methods are limited by cadaveric biofidelity, which is one of the main challenges facing all impact injury biomechanical research (Patton et al., 2013). The purpose of using animal models or cadavers is obviously that this form of research cannot be conducted on live humans. However, as for laboratory studies with dummies, responses of animals and cadavers might not resemble responses of live humans. This limitation should be borne in mind when interpreting results from studies utilising instrumented helmets, crash reconstructions with ATDs and mathematical modelling.

Patton (2016) reviewed the validity of head instrumentation devices, and reported that for some devices, laboratory validation studies found large discrepancies between device measurements and headform data, especially for certain impact directions. Such discrepancies may be a result of nonrigid skull coupling for helmets, headgear, headbands, skullcaps, and skin patches (Patton, 2016). O`Connor et al. (2017) reported from a systematic review of head impact measurement devices that measurements collected by impact monitors provided real-time data to estimate player exposure, but did not have the requisite sensitivity to concussion. They further discussed that head impact-monitoring systems have limited clinical utility due to error rates, designs, and low specificity in predicting concussive injury (O'Connor et al., 2017).

Mathematical modelling

Examples of multi-body human modeling and numerical simulations are mathematical modelling using rigid body and finite element (FE) modelling. According to Krosshaug et al. (2005) the advantage of the simulation approach is that one can study different injury mechanisms in a computer environment, thus avoiding any hazard to athletes. Depending on the models, one can study cause-effect relations, in ACL research for example, between neuromuscular control and knee loading (Krosshaug et al., 2005).

Bailly et al. (2016) used a MADYMO human body model, to reconstruct head impacts from snowboarding back-edge catches, based on the studies of Scher et al. (2006) and Richards et al. (2008) (Figure 8). The damping properties of the snow were evaluated and implemented in the model, and the modelled snow stiffnes was based on outdoor head-form drop tests. They evaluated their model numerically against the experiments performed by Scher et al. (2006) and Richards et al. (2008) (Figure 8). The main results showed that mean experimental peak linear acceleration on hard snow was 72±0.5 g, 93±4.5 g, and 138±6.2 g, respectively, for a 1.5-, 2-, and 3-m drop height. On soft snow the peak linear acceleration was 42±4.8 g, 54.3±2.4 g, and 80.5±12.5 g. Snow stiffness, speed, and snowboarder morphology were the main factors influencing head impact metrics. Mean normal-to-slope head impact speed was 7.8±1.7 m/s and mean tangential impact speed was 3.8±1.9 m/s (Bailly et al., 2016).

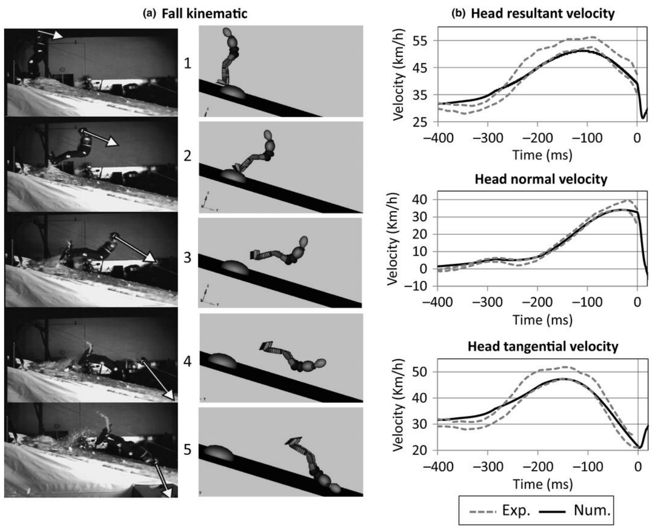

Figure 8. *Kinematics comparison (a) and head resultant (b), normal (c), and tangential (d) velocity comparisons between the ATD reconstructions by Scher et al. 2006 and Richards et al. 2008 (exp.) and multi-body model (num.) by Bailly et al. 2016, during the fall (time zero represents head-to-ground contact). From Bailly et al. (2016). Permission to reproduce image obtained from Scandinavian Journal of Sports Medicine 24.09.17*

Rgid body models and FE models can be combined. For instance, Fréchède et al. (2009) reconstructed 27 concussion cases from the video dataset of McIntosh et al. (2000) using rigid body simulations, to refine the knowledge of the dynamics associated with concussion (Frechede and McIntosh, 2009). Patton et al. (2013) further used the dataset first recorded by McIntosh et al. (2000) and later analysed with rigid body simulations by Frèchède et al. (2009), as input for their FE model (Patton et al., 2013). Patton et al. (2013) found through their FE model that impacts to the temporal regions of the head caused rotations in the frontal plane, which resulted in injurious strain levels in the brain. The strain levels corresponded well with previous results published from FE modelling of American football head impacts, and single axon, optic nerve and brain slice culture model studies (Patton et al., 2013, Viano et al., 2005).

An injury model nearly always needs to be validated, either in a non-injury situation or in vitro, which clearly adds a degree of uncertainty to its use (Krosshaug et al., 2005). Still, the biggest challenge is probably how to verify that the simulated injury pattern actually resembles what is experienced in real life (Krosshaug et al., 2005). For that reason, systematic video analyses of real head injury situations among FIS WC athletes can provide important information for future studies aiming to reconstruct head impact injury cases using mathematical modelling/simulation approaches. To provide information about real head injury mechanisms was therefore an important aim of *Papers II, III and IV*.

Summary of research approaches to describe head injury mechanisms

To better understand the causes of head injuries in skiing and snowboarding, not only the risk factors for injuries, but also the injury mechanisms must be investigated. Many research approaches exist to describe head injury mechanisms in skiing and snowboarding. However, no single approach is without limitations or can answer all research questions. Therefore, a combination of approaches is needed. Most studies have been performed at the recreational level. Interviews, surveys and use of hospital records are commonly used to describe gross injury mechanisms. However, these approaches have limitations, such as recall bias. To provide a more detailed account of the injury mechanisms, studies have utilised biomechanical approaches such as the MBIM technique, dummy studies, mathematical simulations and in vivo measurements (helmet-mounted accelerometers). However, in laboratory-based studies and computer simulations, care must be taken to ensure the external validity of the replicated crash sequences. There has been no systematic video analysis of gross head and face injuries, and only one previous description of gross head impact biomechanics in a real head impact injury situation at the WC level (Yamazaki et al., 2015). Therefore, the aim of *Paper II* of this thesis was to describe the gross head impact injury mechanisms and the aims of *Papers III and IV* were to describe the gross head impact biomechanics in several real injury cases among WC skiers and snowboarders.

Head injury prevention

Helmets

There are two primary injury types that could potentially be avoided using helmets: concussion and more severe head injury (McIntosh et al., 2011). However, current skiing and snowboarding helmets are not designed to prevent concussion, and one of the challenges in designing helmets for preventing concussive forces is accurately replicating concussion risk in the laboratory (Rowson and Duma, 2013). Current helmets are, through their energy-absorbing foam liners, optimised to reduce the linear acceleration of the head and related injuries, such as skull fractures (McIntosh et al., 2011). Since rotational motion is not included in any current skiing or snowboarding helmet testing standard, it is not known to what extent the current helmets reduce the rotational accelerations during a head impact (ASTM:F2040-11, 2011, EN:1077, 2007, Snell:RS-98, 1998). However, helmets can reduce the impact force and as a result also reduce the magnitude of the rotational loads applied to the brain (McIntosh et al., 2011). That means that a helmet can possibly reduce the severity of injury by converting a potentially serious brain injury incident into a concussion or less severe brain injury incident (McIntosh et al., 2011). By attenuating impact energy, current helmets reduce the forces acting on the head that might lead to less severe brain injuries (such as concussions), but helmets alone may not be able to prevent rotational motion of the head that is thought to be linked to the stretching of axons in the brain related to concussion (McIntosh et al., 2011).

Helmet design

A skiing/snowboarding helmet consists of a rigid head covering and a retention system (chin strap). The retention system (strap) holds the helmet in position throughout normal usage and especially during falls and accidents (Snell Memorial Foundation, www.smf.org, accessed 01.07.17) The rigid covering protects the head from direct impact by its capacity to manage impact energy and also by its capacity to spread a concentrated load at its outer surface over a larger area of the wearers head (Snell Memorial Foundation, www.smf.org, accessed 01.07.17). The helmet foam liner (located on the inside of the outer shell) protects the wearer`s head by absorbing the remaining force of the impact that was already partially absorbed and dispersed by the outer shell (Swarén et al., 2013). The foam liner is usually made of lightweight and highly impact-absorbing expanded polystyrene or expanded propylene (Swarén et al., 2013).

Helmet testing

In general, a helmet impact test involves a series of controlled impacts where a helmet is positioned on a metal head form and dropped in a guided fall onto steel test anvils (such as flat, hemisphere, kurbstone, roll bar, edge or a horseshoe type) which simulate different impact surfaces (Figure 9)(Snell Memorial Foundation, www.smf.org accessed 01.07.17). The head forms are instrumented with an accelerometer to measure peak acceleration. The impact energy (drop height and mass), or how hard the helmets are impacted is unique to each standard. The EN 1077 test standard has a pass/fail criterion for peak linear maximum headform acceleration of 250g (g_{max}<250g) in flat anvil impacts at 5.4 m/s. In comparison, the pass/fail criteria in both the ASTM F2040 and Snell RS- 98 standards is 300g peak linear headform acceleration (g_{max}<300g), in 6.2 m/s and 6.3 m/s, respectively, flat anvil impacts (Table 3).

The current standards use a translational-based pass/failure criteria (peak linear acceleration) and criteria that are associated with impact duration, such as e.g. the Head Injury Criterion (HIC)(Connor et al., 2016). The HIC is a severity index, which measures the likelihood of head injury arising from an impact, and is based exclusively on the resultant translational acceleration of the head. This severity index evaluates a helmet`s ability to prevent skull fracture (Rowson and Duma, 2013).

Helmets are predominantly designed for impacts on rigid surfaces (such as roads or pavements) and not for impacts on more compliant surfaces such as snow or ice (Connor et al., 2016). These test surfaces are not designed to simulate real-world conditions, but rather to represent severe impact surfaces that allow helmet performance to be evaluated and facilitate test repeatability and reproducability (Connor et al., 2016). Snow properties had a major influence on resultant accelerations in previous dummy and MADYMO studies reconstructing head impacts on snow (Dressler et al., 2012, Bailly et al., 2016, Scher et al., 2006, Richards et al., 2008). Therefore, to design optimal helmets for elite skiers and snowboarders, future helmets should be developed and evaluated also with regard to realistic impact conditions, such as impacts onto snow and ice (McIntosh et al., 2011).

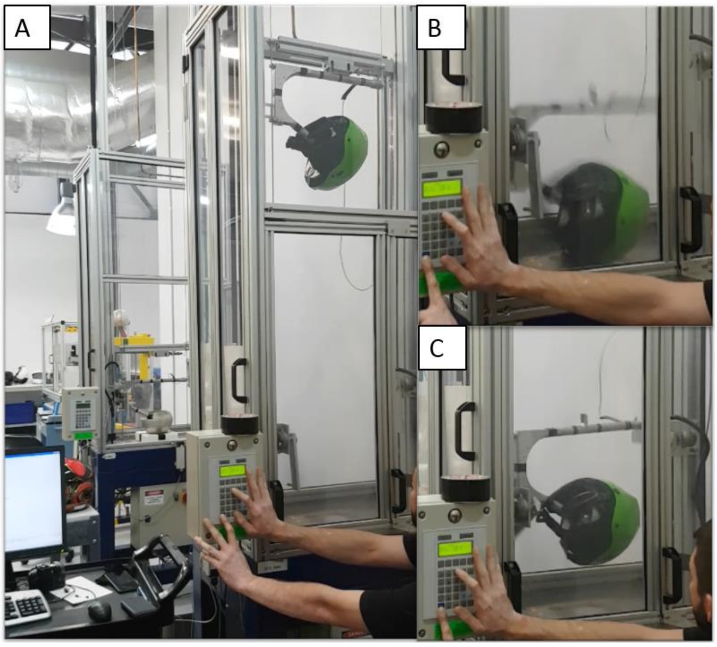

Figure 9. *An example of the laboratory helmet testing procedure (note that this is not a skiing/snowboarding helmet). The method exemplified here is "AS/NZS 2512.3.1:2007, Methods of testing protective helmets Determination of impact energy attenuation - Helmet drop test". A) The helmet is raised to, and dropped from, a specified height so that it will reach a certain resultant impact velocity. B) The helmet impacts the surface or impact anvil. C) The helmet rebounds. (Reproduced with permission from Andrew S. McIntosh, personal communication 24.11.17).*

Helmet standards

At the FIS WC level helmet use is mandatory in all WC and Olympic Winter Games events (FIS-Specifications, 2016). Helmets were previously only designed for recreational skiers and snowboarders, and helmets that addressed the needs of elite athletes were necessary (McIntosh et al., 2011). To adress the fact that elite skiers and snowboarders might need stricter helmet testing standards compared to recreational skiers and snowboarders, FIS enforced a new helmet safety rule for alpine downhill, super-G and giant slalom, and for freestyle ski cross, prior to the 2013/14 WC season (www.fis-ski.com).

In alpine skiers, until the 2013/14 season, helmets had to comply with either the ASTM F2040 or the EN 1077 (class A) standards (Table 3). The new helmet rule was enforced as an attempt to prevent severe head injuries among WC skiers. Under the new FIS safety rule, helmets must be certified under both ASTM F2040 and EN 1077 (class A: full head coverage) standards. In addition, the helmets are required to pass a 6.8 m/s impact energy attenuation drop test using the EN 1077 method (Table 3). The additional test corresponds to a drop height of 2.4 m (FIS-Specifications, 2016). The consequence of the new, stricter helmet rule with respect to helmet design, was that the helmet manufacturers increased the thickness of the energy-absorbing foam liner inside the helmet (Connor et al., 2016). However, this new, stricter rule has not been enforced by FIS for snowboarding or for the other freestyle disciplines (FIS-Specifications, 2016). Since the start of the FIS Injury Surveillance System in 2006/2007, it has been mandatory for snowboard and freestyle skiing helmets to comply with either EN 1077 (Class B) or ASTM F2040, as minimum standards. The EN 1077 Class B standard requires a smaller head coverage area compared to Class A, and does not include a requirement to cover the ears. However, helmets fulfilling higher safety standards such as EN 1077 (Class A) or Snell RS-98 could also be used (FIS-Specifications, 2016).

Table 3. *A summary of the skiing and snowboarding helmet testing standards.*

Standard	Year	Impact surface (anvil)	Drop height (m)	Testing velocity (m/s)	Pass/fail criteria (g_{max})
Snell RS-98	1998	Flat	2.0	6.3	<300g
		Hemi	1.6	5.6	
		Edge	1.6	5.6	
EN 1077: 2007	2007	Flat	1.5	5.4	<250g
ASTM F2040-11	2011	Flat	2.0	6.2	<300g
		Hemi	1.2	4.8	
		Edge	1.0	4.5	
EN 1077: 2007 *Additional test (FIS rule)*	*2013*	*Flat*	*2.4*	*6.8*	*<250g*

Helmet use and risk of head injury

Whereas at the recreational level, the study aims are primarily related to investigating if helmet use is beneficial or not with respect to head injury risk and head injury severity, the FIS WC level differs, as helmet use is mandatory (FIS-Specifications, 2016). Therefore, the aim of this thesis is not concerned with comparing helmet use versus non-use in FIS WC athletes. The relevant question in this case is if the helmets used by elite WC skiers and snowboarders are optimally tested for the impacts at this elite level. This will therefore be the focus of *Papers III and IV*. Until the 2013/14 season, the helmets worn by all FIS WC athletes conformed to the recreational skiing and snowboarding helmet-testing standards, and in snowboarding and all freestyle disciplines except ski cross, they still do. Therefore, it is of interest to discuss the effects of helmets among recreational skiers and snowboarders.

Helmet use and risk of head injury in recreational skiing and snowboarding

Hagel et al. (2005b) reported a 29% reduction in head injury risk for skiers and snowboarders wearing a helmet at 19 ski areas in Canada. They also reported a protective effect of helmets on severe head injuries (defined as requiring evacuation by ambulance) (OR 0.44, 95% CI 0.24–0.81) (Hagel et al., 2005b). Sulheim et al. (2006) conducted a case-control study at 8 major Norwegian alpine resorts during the 2002 winter season. They found that using a helmet was associated with a 60% reduction in the risk for head injury (OR 0.40; 95% CI 0.30-0.55) when comparing skiers with head injuries with uninjured controls. For 147 potentially severe head injuries (referral to an emergency physician or for hospital treatment), the adjusted OR was 0.43 (95% CI, 0.25-0.77). The risk for head injury was higher among snowboarders than for alpine skiers (adjusted OR, 1.53; 95% CI, 1.22-1.91) (Sulheim et al., 2006).

The conclusions of, among others, Sulheim et al. (2006) and Hagel et al. (2005b) resulted in general recommendations to wear a helmet while skiing or snowboarding in many countries. A decade later Sulheim et al. (2017) therefore, performed a follow-up study to determine the effect of the expected increased helmet wear on the risk of head injury (Sulheim et al., 2017). The main findings were that helmet use among injured skiers and snowboarders had increased more than threefold from 2002 (23.8%) to 2011 (77.1%). However, the relative reduction in the proportion of head injuries was smaller than anticipated (from 18% in 2002 to 15% in 2011)(Sulheim et al., 2017). Helmet use was associated with improved odds for head injuries, but this effect was attenuated in 2010 (OR 0.79, 95% CI 0.63 to 0.98), and not significant in 2011 (OR 0.80, 95% CI 0.60 to 1.06) compared to in 2002. For potentially severe head injuries, the protective effect of using a helmet was better sustained over the observation period, from an OR of 0.44 (95% CI 0.28 to 0.68) in 2002 to an OR of 0.74 (95% CI 0.57 to 0.97) in 2010 and 0.67 (95% CI 0.47 to 0.96) in 2011 (Sulheim et al., 2017).

Shealy et al. (2015) found through a prospective longitudinal epidemiological study (1995/1996 to 2011/2012) of recreational skiers, where the incidence of helmet usage increased from 8% to

84% during the study period, that during the 17 seasons, the prevalence of all injuries to the head decreased from 8.4 to 6.8 %. The prevalence of potentially serious head injuries decreased from 4.2 to 3.0 %. However, neither prevalence change in itself was significant (Shealy et al., 2015).

According to the above studies, while helmet use has increased dramatically over the last decade, there has not been an equally dramatic reduction in rates of head injuries at the recreational level. Still, the risk of head injuries, and importantly, for potentially severe head injuries, has been reduced among helmet users during this period. Therefore, according to Sulheim et al. (2017) wearing a helmet should be strongly recommended.

However, two recent prospective cohort studies found that despite the fact that helmet use has increased greatly during the 2000-2011 time-period, there was no reduction in the number of TBIs among Swiss recreational skiers or snowboarders (Baschera et al., 2015, Hasler et al., 2015). Hasler et al. (2015) reported no change in the TBI rate of snowboarders during the studied period, although helmet use increased from 10% to 69%. Comparing snowboarders with and without a helmet showed no significant difference in the OR for the severity of TBI, however, the OR for off-piste compared with on-slope snowboarders was 26.5 ($p = 0.003$) for sustaining a moderate-to-severe TBI (Hasler et al., 2015). Baschera et al. (2015) compared TBI in skiers with or without a helmet and reported an adjusted OR of 1.44 ($p=0.430$) for suffering moderate-to-severe head injury in helmet users. Comparison of off-piste to on-slope skiers revealed a significantly increased OR among off-piste skiers of 7.62 ($p=0.004$) for sustaining a TBI requiring surgical intervention (Baschera et al., 2015).

Investigating the effect of helmets on severe head injuries, Fukuda et al. (2007) compared snowboarders wearing a helmet, a knit cap and no cap. Severe head injury was highest in the helmet wearers ($p=0.0001$). After adjusting for jumping, they reported a nonsignificant effect of helmet use on severe head injuries (compared with nonserious head injuries) (OR 0.66, 95% CI 0.32–1.35) (Fukuda et al., 2007).

The somewhat inconsistent findings between studies warrants further discussion. To attempt to understand the discrepancies, it is relevant to highlight current discussions regarding risk factors for head injuries.

Helmet use as risk factor for head injuries?

One ongoing discussion of risk factors in recreational snowboarders and skiers, is if helmet use is an extrinsic risk factor for head injury. This is mainly based on a risk-compensation hypothesis, which means that skiers/snowboarders may take higher risk runs or have more risky behaviour when they wear a helmet, which means that they experience changes in behaviour resulting from the introduction of a safety measure (Ruedl et al., 2015, Bahr and Krosshaug, 2005). In addition, Stieg & Perrine (2016) suggested that helmets may have the opposite effect than intended, and increase risk taking behavior during sports because of the belief that the helmet will protect against concussions.

However, the basis for the risk compensation hypothesis in recreational skiing and snowboarding is unclear. In support of the risk-compensation hypothesis, Ružić & Tudor (2011) reported that helmeted males skiers took significantly higher risk, while this was not the case for female helmeted skiers (Ružić and Tudor, 2011).

Scott et al. (2007) found no evidence of risk compensation among helmeted skiers and snowboarders. Contradictory to the risk-compensation hypothesis, they concluded that the decision to wear a helmet may be part of a risk reduction orientation (Scott et al., 2007). Hasler et al. (2010) reported that not wearing a helmet and riding on icy slopes emerged as a combination of risk factors associated with injury. Hagel et al. (2005a) found no evidence that helmet use increased the risk of severe injury to other body parts than the head/neck, or increased high-energy crash circumstances in skiers and snowboarders (Hagel et al., 2005a). Ruedl et al. (2012) reported that ski helmet use was not predictive of a more risky behaviour. Self-reported risk taking and self-reported risk compensation were associated with having a sensation seeking personality trait. Therefore, the personality trait of being a sensation seeker, not the wearing of a ski helmet, was associated with riskier behaviour on the ski slopes (Ruedl et al., 2012).

Sulheim et al. (2017) showed that there was an increase in the number and proportion of injured persons in terrain park areas from 2002 to 2011. In the same period, the proportion of expert and good skiers increased, so they suggested that an increased number of skilled skiers performing more risky moves led to an increased injury risk in snow parks over the observed decade (Sulheim et al., 2017). However, despite the trend for higher relative injury risks in park areas, the risk of head injury cases compared to controls over the actual period decreased (Sulheim et al., 2017). Hasler et al. (2015) and Baschera et al. (2015) identified going off-piste as a risk factor for head injury. Perhaps crashes in terrain parks and off-piste are linked to manoeuvres performed and events occurring in these locations, therefore, rather than risk-compensation due to helmet wear (Brooks et al., 2010, Russell et al., 2014).

The risk-compensation hypothesis regarding helmet wear could be irrelevant for the WC athletes covered in this project though, since helmet wear was not introduced recently, and all data included in this thesis covers a period where helmet use has been mandatory for all athletes. In addition, athletes in all disciplines who are now at the FIS WC level must all have been FIS-level racers previously, where helmet use is also mandatory. This means that for these athletes, helmet use is not novel, but something they are used to, during competitions at least. However, one specific safety measure that has been recently changed (prior to the 2013/14 season) at the FIS WC level, is a stricter helmet testing rule for alpine downhill, super-G, giant slalom and freestyle ski cross. If this stricter helmet-testing standard has resulted in risk compensation among eligible FIS WC athletes is unknown.

Summary head injury prevention and helmets

Helmet use has increased greatly over the last 15 years, but the rate of head injuries has not decreased to a similar extent. However, head injuries and severe head injuries in particular, may still have decreased, and helmet use is strongly recommended. Helmets are designed to prevent head injuries, but specifically, due to the testing criteria based on linear acceleration measures, to prevent skull fractures. Angular motions are not included in any current skiing and snowboarding helmet-testing criteria. Skiing and snowboarding helmets are not specifically designed to prevent concussions, but may have the capacity to transfer the burden of energy on the brain from a severe TBI to a concussive incident. The current highest helmet testing velocity for WC giant slalom, super-G, downhill and ski cross is 6.8 m/s under the EN 1077 test-method. Whether this testing speed reflects real head impact injury situations on snow is unclear. Therefore, we aimed to investigate the head impact kinematics of real head injury situations among FIS WC skiers and snowboarders in *Papers III and IV*.

Aims of the thesis

I. To investigate the incidence of head injuries, including the severity and the types of injuries, in the different World Cup alpine, freestyle and snowboarding disciplines, in addition to examining any sex differences in head injury risk

II. To systematically analyse head and face injuries recorded by the FIS Injury Surveillance System through ten seasons (2006-2016) of World Cup alpine and freestyle skiing and snowboarding to describe their mechanisms

III. To describe the gross head impact biomechanics, and to compare the head impact characteristics with relevant helmet standards in a selection of head impact injury cases amongst WC alpine, snowboard and freestyle athletes

Methods

This thesis is based on four papers concerning head and face injuries in FIS WC alpine and freestyle skiers and snowboarders, based on data from the FIS Injury Surveillance System (ISS) from 2006-2016. In *Paper I* we investigated the epidemiology of head and face injuries among WC alpine and freestyle skiers and snowboarders, in *Paper II* we performed a systematic qualitative video analysis of head and face injury mechanisms, and in *Papers III and IV* we used a 2D video-based motion analysis approach to reconstruct real head impact injury situations from broadcast video.

Injury registration (Papers I-IV)

All injuries were recorded through the FIS Injury Surveillance System (ISS) based on annual retrospective athlete interviews. In *Paper I*, we included injury data from seven seasons (2006-2013), in *Paper II* we included injury data from ten seasons (2006-2016), in *Paper III* from eight seasons (2006-2014), and in *Paper IV* from nine seasons (2006-2015). The only exception is Case 4 in *Paper III* where we obtained medical information from the IOC injury and illness surveillance system for multi-sport events, used during the 2014 Winter Olympic Games in Sochi, Russia (Soligard et al., 2015).

WC athletes were interviewed at the WC finals at the end of each season. The WC season was defined as starting at the first WC competition of the season (usually October for alpine skiers, and August for freestyle skiers and snowboarders) and ending at the last WC competition of the season (usually at the end of March), resulting in a 5-month to 7-month WC season. If an athlete was not present at the event, due to injury or other reason, or if the athlete did not understand English, the team coach, physician or physiotherapist was interviewed. The team had to have a response rate of ≥80% to be included. All athletes included were registered in the FIS database, had started in at least one FIS WC competition and had to be confirmed by the team coach as a member of the official WC team. The team coaches reviewed our lists of athletes to confirm which athletes belonged to the official WC team and added athletes if any were missing from our lists.

All interviews were conducted in person by physicians or physiotherapists from the Oslo Sports Trauma Research Center in the finishing area, after team captains' meetings or during organised meetings at the competitors' hotels. We completed a standardised interview form for each athlete, where the athlete consented to participate in the FIS ISS (Appendix 1).

Injury definition (Papers I-IV)

If the athlete reported an injury, a specific injury form was completed for each injury (Appendix 2). We defined injuries as "all acute injuries that occurred during training or competition and required attention by medical personnel." The injury form included information about the date and place of injury, injury circumstances, body part injured, side (left/right), injury type, injury severity and the specific diagnosis. The injury definition and the classification of injury information was based on a consensus document on injury surveillance in football (Fuller et al., 2006).

Head injuries were classified as 'head/face' injuries and did not include neck or cervical spine injuries. Injury type was classified as fractures and bone stress, joint (non-bone) and ligament, muscle and tendon, contusions, lacerations and skin lesions, nervous system including concussion, other injury or no information available. We also recorded the specific diagnosis. Injury severity was classified according to the duration of absence from training and competition as follows: slight (no absence), minimal (1–3 days), mild (4–7 days), moderate (8–28 days) and severe (>28 days).(Flørenes et al., 2011) This classification of injury severity is an operational injury definition within the FIS ISS (where all injuries and not only head/face injuries are registered), and therefore not a head injury specific definition of severity.

Exposure registration (Paper I)

To calculate exposure, we obtained the exact number of started runs by each of the athletes interviewed from the official FIS competition website (http://www.fis-ski.com) for each of the seven seasons (2006–2013). The result lists for each of the WC, World Ski/Snowboard Championships (WSC) and Olympic Winter Games (OWG) competitions during the seven seasons were extracted one by one from the FIS website into an Excel file. Specific variables were added to the result for each of the athletes, that is, date, discipline, place and sex. In addition, we created a new variable to calculate the number of started runs for each athlete per competition. The exposure data were transferred to our database (Oracle Database 11 g, Oracle Corporation, California, USA) and linked to the injury data recorded through the interviews. We calculated total exposure, as well as exposure for men versus women and for each of the different snowboarding, freestyle and alpine subdisciplines

Video aquisition (Papers II, III and IV)

All videos from FIS WC competitions were collected retrospectively at the end of each of the 8, 9 or 10 seasons from the FIS WC television producer (Infront Media). As only competition runs are filmed by the television producer, no videos of warm-up runs, and only one video of an official training run, were acquired. Videos were obtained from the IOC Olympic Multimedia Library in cases where the injuries occurred during OWG competitions.

In *Paper II,* of the 123 injury cases, we obtained 57 injuries on video with the possibility of analysing the gross head injury mechanism (alpine n=29, snowboard n=13, freestyle n=15) (Figure 10).

In *Papers III and IV,* the main criterion for including the videos was a primarily sagittal view of the athlete during the head impact incident. This was necessary to obtain as accurate results as possible from the 2D motion analysis software. In *Paper III*, of the 16 available videos of competition injuries, only 4 met this criterion. All cases had one visible head impact that we could analyse. In *Paper IV,* 27 videos were obtained and reviewed for suitability. In addition, we obtained 1 video from an official WC training run. In total, we therefore obtained 28 videos. Of the 28 videos obtained, only 7 met the inclusion criterion of a primarily sagittal view of the head impact. Of the 7 suitable videos, two cases had 2 head impacts. In the remaining cases the athlete had 1 head impact, allowing us to analyse 9 head impacts from 7 cases. In total therefore, in *Papers III* and *IV* we could analyse 13 head impacts from 11 injury cases with the 2D motion analysis software.

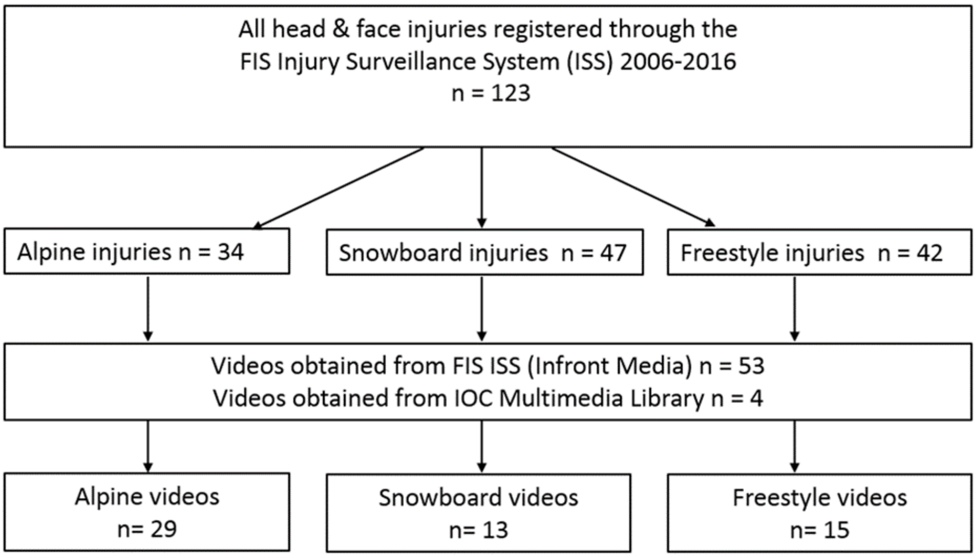

Figure 10. *The video aquisition process of Paper II.*

Video processing (Papers II, III and IV)

In *Paper II* the 57 videos were converted to mp4 file format with H.264 encoding using Adobe Premiere Pro version CS6 (Adobe Systems Inc. San Jose, CA), and viewed using the frame-by-frame function in Quicktime version 7.7.9 (Apple, Cupertino, California). The videos had frame rates of 25 Hz, 50 Hz and 60 Hz and the display aspect ratios were 4:3 or 16:9.

In *Papers III and IV,* two of the videos obtained had a progressive scan with a frame rate of 25 Hz, while nine of the videos were obtained in an interlaced format, making it possible to double the effective frame rate to 50 Hz and 60 Hz. All videos in *Papers III and IV* were edited and deinterlaced using Adobe premiere Pro CS6 (Adobe Systems Inc. San Jose, CA). We edited the videos to obtain square pixels (1:1 pixel aspect ratio).

Qualitative video analysis (Paper II)

For the qualitative video analysis we developed a specific analysis form for head/face injuries based on previous analysis forms used for analysis of injuries in alpine skiing and snowboard cross (Bere et al., 2014a, Bere et al., 2011a, Bakken et al., 2011). The analysis form included closed questions regarding: a) the skiing/riding situation and gross body biomechanics pre-injury,

b) analysis of the head impact in detail and c) post-injury security net contact. In addition, there was one open question where analysts were asked to describe the head injury mechanism in their own words *(video analysis form- Appendix 3)*.

Five expert analysts in the fields of sports medicine or head injury biomechanics formed the analysis team. Initially, injury videos for each case were analysed independently using the form. During this phase, all analysts were blinded to the opinions of others, but were provided with injury information on each case (sex, discipline and specific diagnosis). The primary investigator then summarised the analysis forms from all five analysts. Consensus was said to have been reached if at least three analysts selected the same response. Cases for which consensus was not reached were discussed during a meeting attended by all experts. During the meeting, injury videos were reviewed as many times as required to obtain agreement.

Head impact injury reconstruction from broadcast video (Papers III and IV)

A commercial software programme for videobased movement analysis (SkillSpector, Version 1.3.2, Odense, Denmark) was used to digitize a fixed point on the helmet, as well as two reference points in the surroundings (Figure 11).

Figure 11. *From Case 2, Paper III. Illustrating the digitized head point and two reference points in the surroundings*

Linear kinematic analysis

We used a smoothing spline algorithm with a 15 Hz cut-off to calculate head velocity (Woltring, 1986). To determine the change in linear velocity in the normal-to-slope and along-slope directions, we extracted variables from pre-impact and post-impact frames, immediately before and after (maximum 4 frames (80 ms)) the head impact. The lowest downwards velocity immediately pre-impact was reported, in addition to the highest upwards velocity immediately post-impact (Figure12).

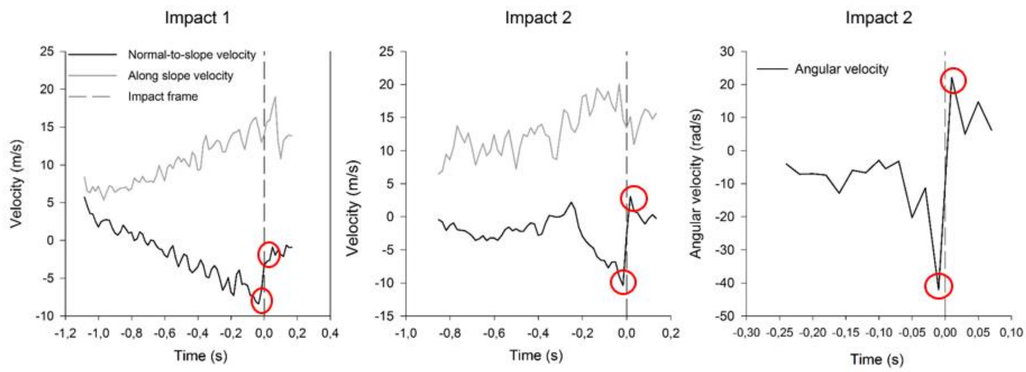

Figure 12. *An example of how we extracted the variables for the preimpact and postimpact velocity, shown by the red circles on the normal-to-slope linear velocity curves and on the angular velocity curve. From Paper IV, Case 1, impacts 1 and 2 (60 Hz), showing the linear velocity (m/s) of case 1, impact 1 and linear velocity (m/s) and angular velocity (rad/s) of case 1, impact 2.*

Angular kinematic analysis

We measured the sagittal plane angular velocity of the helmet frame by frame, from at least 10 frames pre-impact to at least 5 frames post-impact, using an angle measurement software (MB Ruler version 5.3, © Markus Bader - MB-Softwaresolutions). In *Paper III* we aligned the MB Ruler visually with an estimated alignment close to the Frankfurt plane, represented by the goggle band, on a frame by frame basis (Figure 13). In *Paper IV* we aligned the MB Ruler visually with an estimated alignment from the chin to the estimated midpoint of the top of the helmet on a frame-by-frame basis.We did three trials for each case and we report the mean angular velocity (±SD). Angular velocity was estimated as the change in angle between two frames divided by the time interval. We did not filter the angular velocity. To estimate the change in angular velocity we used the lowest negative point of the pre-impact angular velocity and the peak of the post-impact angular velocity (maximally 4 frames (80 ms or less) before and after the impact) (Figure 12).

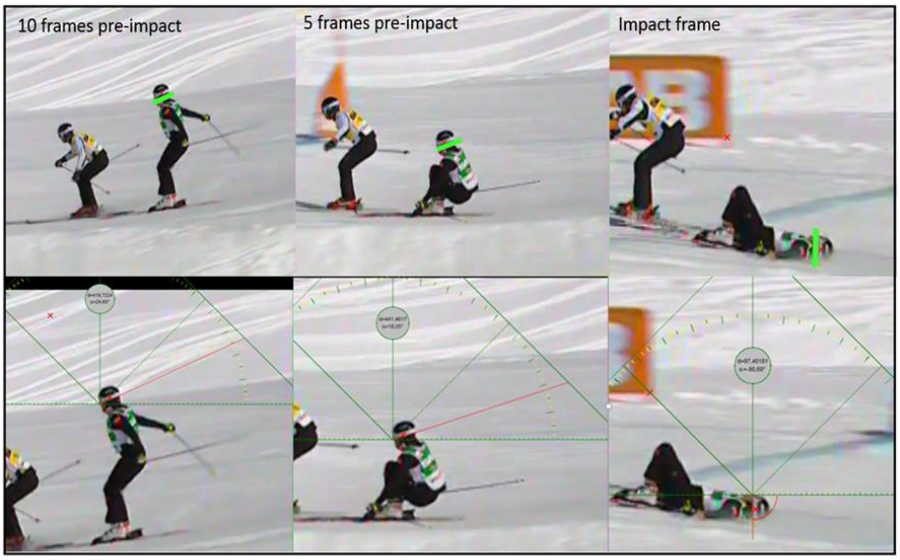

Figure 13. *An example of how we performed the angular measurement of the helmet, frame by frame with the MB Ruler. From Case 2, Paper III.*

Video calibration

We obtained the ski or snowboard dimensions from the athlete or their ski/snowboard supplier. We created a local calibration frame that was oriented with axes along and normal to the slope of the surface during the head impact (Figure 14). We assumed that the vertical direction of the video footage was aligned with the true vertical axis. The local calibration frame was positioned at the frame of head impact, using the length of the skis or snowboard for scaling. (Figure 14). In *Paper III*, the ski/snowboard lengths ranged between 150 cm and 191 cm. Based on this information we could calculate the pixel size to range from 0.8 cm to 1.3 cm. The pixel size was calculated at the ski/snowboard measurement frame. The measurement of the ski/snowboard was performed at the closest possible frame to the frame of impact where we could see the ski/snowboard perpendicularly and in full length. As we could not see the ski/snowboard perpendicularly and in full length during the head impact frame in any of the cases, the measurement frame is therefore not the same as the calibration frame. The mean time from the measurement frame to the calibration frame for all 4 cases was 0.3 s.

In *Paper IV*, in 3 head impacts (case 1- impact 1, case 4, case 6-impact 1), the measurement frame was the same as the calibration frame. For the remaining 6 head impacts, we could not see the ski perpendicularly and in full length during the head impact frame, and the measurement frame was therefore different from the calibration frame. The mean time from the measurement frame to the calibration frame for these 6 impacts was 0.13 s. The ski lengths ranged from 210 cm to 216 cm, corresponding to a range from 78 to 268 pixels (mean 172), with corresponding pixel lengths ranging from 0.4 to 1.3 cm (mean 0.8 cm).

Figure 14. *Illustrating the ski measurement frame and the frame used for the slope calibration, for the digitization of the head point. From Case 2, Paper III.*

For the digitization of the pelvis it was possible to perform the ski/snowboard measurement and the calibration in the same frame. The local calibration frame was aligned with the video image (Figure 15).

Figure 15. *Illustrating the ski measurement frame and the calibration frame, for the digitization of the pelvis. The calibration frame is in line with the video image. From Case 2, Paper III.*

Statistics (Papers I and II)

In *Paper 1,* the injury rate was expressed as the absolute injury rate (number of injuries per 100 athletes per season) and the relative injury rate (number of injuries per 1000 competition runs). When calculating the absolute injury rate, we included all recorded injuries during all training and competitions throughout the seasons, while we only included injuries in WC, WSC and OWG competitions when calculating the relative injury rate, as exposure data (the number of runs started) were only available for these events. The WC, WSC and OWG exposure calculation includes competition runs (qualification and final runs) only, not official training runs. Calculations were based on the Poisson model, and Z tests were used to compare the injury rate between groups. Injury incidences and risk ratios (RR) were presented with 95% CI.

In *Paper II,* we performed a Mann-Whitney U test to assess whether there was any difference in injury severity between the head/face injury cases analysed and the cases where we could not obtain videos. To investigate the association between the number of head impacts and injury severity, a chi square test was performed, assuming linear by linear association. To achieve sufficient statistical power, we regrouped the number of head impacts into the following categories: 1 impact, 2 impacts, 3 or more impacts, excluding cases where the number of impacts could not be assessed. We used IBM SPSS Statistics 24 (Armonk, New York, USA) for the analyses. For all statistical tests, a two-sided alpha level of ≤ 0.05 was considered statistically significant.

Error estimates (Papers III and IV)

The primary investigator performed 3 digitizing trials of the helmet for each case and we reported the mean ± standard deviation (SD) of 3 trials. As a measure of the intra-rater digitizing error, we calculated the root mean square error (cm) of the helmet position (normal and along slope) between the 3 digitizing trials for all cases, and reported the mean. For the eligible cases, we reported the root mean square error (m/s) from the regression line of the flight phases in both the vertical and horizontal directions and the estimated vertical and horizontal acceleration of the estimated centre of mass (represented by the pelvis) due to gravity during the flight phases. In addition, we reported the root mean square error (degrees) of the 3 trials of the angular measurement of the helmet in the eligible cases.

Ethics

The study was reviewed by the Regional Committee for Medical Research Ethics, South Eastern Norway Regional Health Authority, Norway

Results and discussion

Epidemiology (Paper I)

During seven WC seasons (2006-2013), 2080 injuries (snowboard n = 749, freestyle n = 668, alpine n = 663) were reported among 5247 interviewed athletes (Table 4). Of these, 245 (11.8%) were head/face injuries. The most common injury type was classified as nervous system injuries/concussions (n=200, 81.6%), and of these, all were reported to us with a diagnosis of concussion (Table 5).

Table 4. *The number of athletes interviewed in FIS World Cup alpine skiing, freestyle skiing and snowboarding for each of the 7 seasons (2006-13) among males and females.*

	Snowboard		Freestyle		Alpine		
Season	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Total**
2006/07	92	50	107	46	144	116	555
2007/08	186	94	177	86	148	113	804
2008/09	173	96	143	103	148	115	778
2009/10	172	99	96	56	140	128	691
2010/11	202	113	171	105	157	118	866
2011/12	102	54	89	53	148	118	564
2012/13	238	125	207	132	163	124	989
Total	1165	631	990	581	1048	832	5247

Table 5. *Distribution of injury types for head/face injuries (n= 245) reported during 7 seasons (2006-13) of the FIS World Cup, during competition and training, for snowboard, freestyle skiing and alpine skiing.*

		Head/face injury types						
Discipline	**Sex**	**Nervous system including concussion**	**Laceration/ skin lesion**	**Fractures/ bone stress**	**Contusions**	**Muscle and tendon**	**Other**	**Total (n)**
Snowboard	Males	40	1	0	0	1	0	42
	Females	39	3	1	5	0	0	48
	Total	79	4	1	5	1	0	90
Freestyle	Males	41	2	1	1	0	1	46
	Females	35	2	4	0	0	2	43
	Total	76	4	5	1	0	3	89
Alpine	Males	27	4	3	2	0	0	36
	Females	18	7	2	1	0	2	30
	Total	45	11	5	3	0	2	66
Total (n, %)		200 (81.6)	19 (7.8)	11 (4.5)	9 (3.7)	1 (0.4)	5 (2.0)	245

Disciplines

The overall incidence (number of injuries per 100 athletes per season) of head/face injuries (n=245) was higher in freestyle (5.7, 95% CI 4.5 to 6.8) and snowboard (5.0, 95% CI 4.0 to 6.0) compared with alpine skiing (3.5, 95% CI 2.7 to 4.4; RR 1.61, 95% CI 1.17 to 2.22 vs freestyle; RR 1.43, 95% CI 1.04 to 1.96 vs snowboard). The incidence of head/face injuries (n=96) in WC, WSC and OWG competitions (number of injuries per 1000 runs) was also significantly higher in freestyle (1.8, 95% CI 1.2 to 2.4) than in alpine skiing (0.9, 95% CI 0.6 to 1.2; RR 2.05, 95% CI 1.25 to 3.46) and snowboard (1.0, 95% CI 0.6 to 1.3; RR 1.85, 95% CI 1.15 to 2.99).

Since all freestyle disciplines include aerial elements, our findings were not surprising, as previous research from recreational skiing and snowboarding has reported that head injuries may be linked to jumping and acrobatic activities (Russell et al., 2014, Carus and Escorihuela, 2016b, Russell et al., 2013, Carus and Escorihuela, 2016a). In alpine skiing, athletes can reach extremely high speeds (up to 140 km/h in downhill (Yamazaki et al., 2015)); nonetheless, our findings suggest that the incidence of head injury was not necessarily related to initial skiing speed alone, but rather the type of manouvre the athlete was doing or the use of elements. These findings therefore warranted further investigation into the causes of head injuries (the injury mechanisms), which was the focus of *Papers II-IV*.

Sex differences

The overall incidence of head/face injuries was greater for women compared to men per 100 athletes, but not during WC competitions (per 1000 WC runs) (Table 6). When only WC competition injuries are included in the analysis, the number of injured athletes in each category decreases. The low number in each category limits our ability to detect statistical differences between groups, in this case, between males and females in the different disciplines.

Freestyle and snowboard women had a higher injury incidence compared to men (per 100 athletes), while no sex difference was found in alpine skiing (Table 6). Freestyle and snowboard men and women share courses and therefore compete under the same conditions. Sharing the same course does not necessarily mean that men and women perform the same tricks or attain the same speeds or jumping heights, however. Men perform more challenging tricks than women, and attain higher speeds in, for example, ski cross and snowboard cross (McCrory et al., 2013b). Nevertheless, it could be hypothesised that courses and course elements designed to challenge the best male athletes may be too challenging for some women.

In WC alpine skiing, males and females have separate race circuits, which means that they do not share the same courses. According to FIS regulations, male athletes have more challenging courses (including the length, vertical drop and number of gates) than females (FIS-Specifications, 2016). The lack of sex differences in head injury risk in the alpine WC may therefore reflect the fact that male and female athletes have courses more suited to their skill and/or ability.

As our findings were based on epidemiological data alone, we could not draw conclusions regarding why there were sex differences in freestyle and snowboard, but not in alpine, or if there are issues relating to the courses being too challenging for female athletes.

Table 6. *Sex differences in the incidence of head/face injuries for snowboarders, freestyle and alpine skiers during 7 seasons (2006-13) of the FIS WC*

	Males	Females	Risk Ratio (95% CI)
	All head/face injuries (n= 245)		
	Incidence (injuries per 100 athletes) with 95% CI		
Total all disciplines	3.9 (3.2 to 4.6)	5.8 (4.8 to 6.9)	1.48 (1.15 to 1.90)*
Snowboard	3.8 (2.7 to 4.9)	7.3 (5.2 to 9.4)	1.93 (1.27 to 2.91)*
Freestyle	4.5 (3.2 to 5.9)	7.4 (5.2 to 9.6)	1.63 (1.07 to 2.47)*
Alpine	3.4 (2.3 to 4.6)	3.6 (2.3 to 4.9)	1.05 (0.65 to 1.70)
	WC, WSC and OWG head/face injuries (n= 96)		
	Incidence (injuries per 1000 runs) with 95% CI		
Total all disciplines	1.0 (0.7 to 1.2)	1.4 (1.0 to 1.8)	1.47 (0.98 to 2.20)
Snowboard	0.9 (0.5 to 1.3)	1.2 (0.6 to 1.8)	1.39 (0.69 to 2.78)
Freestyle	1.5 (0.8 to 2.2)	2.4 (1.3 to 3.5)	1.59 (0.82 to 3.09)
Alpine	0.7 (0.3 to 1.1)	1.1 (0.6 to 1.6)	1.55 (0.74 to 3.26)

*significant at $p \leq 0.05$

Gross head impact injury mechanisms (Paper II)

In alpine skiing, most of the cases were from the speed disciplines downhill (n=14) and super-G (n=11), followed by the technical disciplines giant slalom (n=2) and slalom (n=2). In snowboarding, the injuries occurred in snowboard cross (n=12) and slopestyle (n=1), whereas in freestyle skiing, the injuries occurred in ski cross (n=10), aerials (n=3), halfpipe (n=1) and slopestyle (n=1). There were 32 male (56%) and 25 female (44%) injured athletes. The age (mean ± SD) of the athletes at the time of injury for alpine skiers, freestyle skiers and snowboarders was 27.0±5.7, 22.1±3.0 and 23.7±2.9, respectively. The most common diagnoses, across all disciplines, were concussions (n=39, 68%), followed by head/face fractures (n=6, 11%), and contusions (n=6, 11%) (detailed medical information, Appendix 4). The injuries were classified as severe in 14 cases (25%), moderate in 15 (26%) and mild in 12 cases (21%). There was no significant (p=0.065) difference in injury severity between the head/face injury cases analysed (n=57) and the injury cases where we could not obtain videos (n=66).

Analysis of the main head impact

Of the 57 videos analysed, most injury cases had one (n=27, 47%) or two (n=16, 28%) visible head impacts, and the first head impact was considered to be the main head impact in the majority of cases (n=41, 71 %). Among alpine skiers, 21% (n=6) of athletes experienced more than two head impacts. We could not assess the number of head impacts in eight cases (14%). There was no association between the number of head impacts and injury severity (p=0.26).

Table 7. *Impact location on the helmet (n=57).*

Discipline	Impact location				
	Face/front	Top	Side	Back	Not visible
Alpine	3	2	10	11	3
Snowboard	2	0	0	9	2
Freestyle	4	0	1	6	4
Total (n)	9	2	11	26	9

The most common impact location was the rear of the helmet (46%), followed by the side (19%), the face or frontal part of the helmet (16%) and the top (4%) (Table 7). Most helmet impacts were on snow (n=47, 83%) and on a downward slope (n=36, 63%) (Figure 16). In more than half of the cases, the helmet slid along the surface post-impact (n=29, 51%). In three alpine skiing cases (10%), the helmet ejected during the head impact. No helmet ejections were observed in the snowboard or freestyle cases. From the visual analysis, the cause of the helmet ejections cannot be determined. It could be that the helmet did not fit adequately, was not securely fastened or that the loads of the crash exceeded the stability of the helmet/strap.

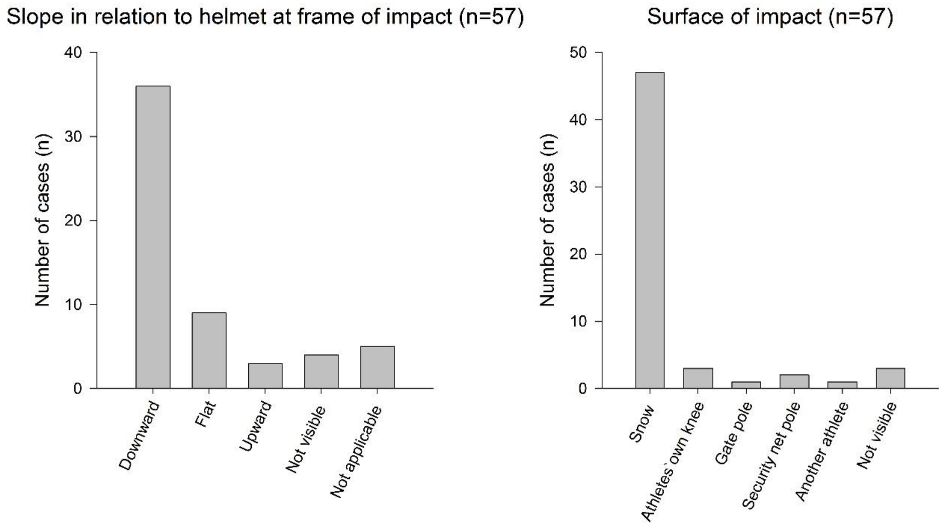

Figure 16. *Analysis of the head impact frame (all disciplines, n=57).*

One of the main requirements of a helmet is to provide and maintain appropriate and adequate coverage to the head, and a helmet that is poorly fitted or fastened may become displaced during normal use or even ejected during a crash (Thai et al., 2015b). Among cyclists, a recent study investigated the fit of helmets and reported that bicycle helmets worn by recreational and commuter cyclists are often the wrong size and often worn and adjusted incorrectly (Thai et al., 2015a). In addition, among motorcyclists, helmet type and wearing correctness were among the factors that affected the loads at which helmets became displaced (Thai et al., 2015b). However, the athletes in the current study were supported by professional teams, and therefore likely received optimal advice and optimally fitted helmets from their equipment suppliers. Therefore, the helmet ejections observed represent a concern. Alpine ski helmets have been demonstrated to provide protection against low-severity repetitive impacts, such as impacting slalom gates (Swarén et al., 2013). However, ski helmet liner materials exhibit degradation in performance for substantial repetitive impacts (Stewart and Young, 2010). The fact that 21% of alpine skiers received more than two head impacts may therefore be an important consideration for helmet manufacturers with respect to helmet design and construction, although we did not detect an association between the number of head impacts and injury severity. However, we do not know whether the helmets used had suffered previous impacts.

Common crash sequence across disciplines

We identified a common crash sequence across disciplines, where most athletes (n = 48, 84 %) impacted the snow with the skis or board first, followed by the upper or lower extremities, buttocks/pelvis, back and, finally, the head (Figure 18, Figure 19). The gross body biomechanics during the crash sequence are important to consider, as this could potentially help increase the ecological validity of future reconstructions of head injury situations. For example, in a previous laboratory reconstruction of snowboarding back edge catches with ATDs, Richards et al. (2008) discussed what they referred to as a "whipping" mechanism. After catching the back edge, the ATD entered an airborne phase and the torso began to angulate as a result of loads coupled through the hip joint. The angular velocity of the torso exceeded that of the lower extremities, resulting in overall extension of the body at the hip joints. As the fall event progressed, coupling through the neck resulted in a whipping motion of the head. The position of the ATD at head impact was in full body extension, with the board in the air. The ATD landed directly onto the head (Richards et al., 2008).

In the MADYMO reconstructions by Bailly et al. (2016) initial riding velocity influenced both fall kinematics and head impact location. At 4.2 m/s initial riding velocity, the buttocks were the first body part to impact the snow, at 9.7 m/s and 14 m/s, the head struck first, with the hips and spine extended (Bailly et al., 2016).

As we observed a common crash sequence (impacting skis/board first, extremities, buttocks/pelvis, back, head) in 84 % of crashes in total across disciplines (Figure 18, Figure 19), it would be interesting to investigate any potential "whipping" head injury mechanism as described by Richards et al. (2008) further, based on this crash sequence. The identification of this crash sequence may also be important for further development of wearable ski-racing airbags, specifically in relation to airbag deployment, i.e. the triggering algorithm. Airbags were first used in official FIS WC races in the 2015/2016 season. However, further design improvements may be possible, particularly with respect to protecting the cervical spine and head in backward pitching falls, such as described in the following sections.

Alpine gross head injury mechanisms

Prior to the head impact situation, the majority of alpine skiers were turning (n=16, 55%) or landing after a jump (n=9, 31%). In all cases (n=29), the athlete made a personal technical or tactical mistake, leading to an out of balance situation. In 12 cases (41%), the athlete had inappropriate gate contact prior to crashing, causing the injury situation. The most common mechanisms of falling were sideways (n=13, 45%) or backward falls (n=10, 35%), followed by forward falls (n=4, 14%) or collisions (n=2, 7%) (Figure 17).

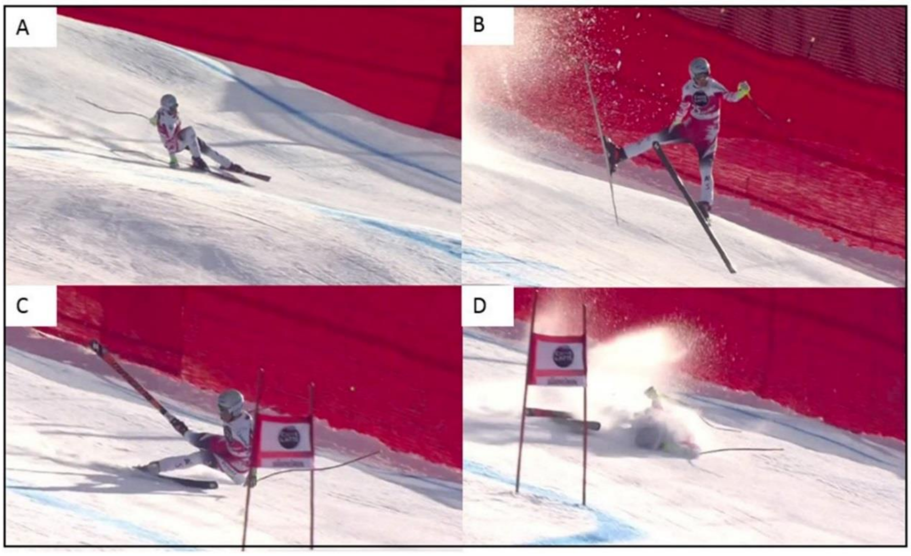

Figure 17. *Alpine skier, typical example of a sideways fall. Key crash events: A) The athlete is out of balance inwards and backwards after a jump. He loses pressure on the outer ski, which then catches the snow. B-C) He hits a new bump, becomes airborne and yaws to the right, rolls to the left and pitches backwards. D) The athlete lands on his left side and impacts the left side of the helmet (impact frame).*

Snowboard gross head injury mechanisms

Prior to the head impact situation, the snowboarders were landing after a jump (n= 5, 39%), bank turning (n= 2, 15%), in between elements (n= 2, 15%) or had already crashed/fallen (n= 3, 23%). A personal technical or tactical mistake contributed to the injury situation in 8 (62%) cases. One athlete had inappropriate gate contact, which was the cause of injury. In 5 (39%) snowboard cross cases, the athlete made a forced error caused by contact with an opponent. Over half (n=8, 62%) of the snowboarders caught the back edge of the snowboard prior to head impact (Figure 21). Snowboarders primarily fell backwards (n=10, 77%); however, 2 fell forwards (15%) and 1 collided with another athlete (8%) (Figure 18).

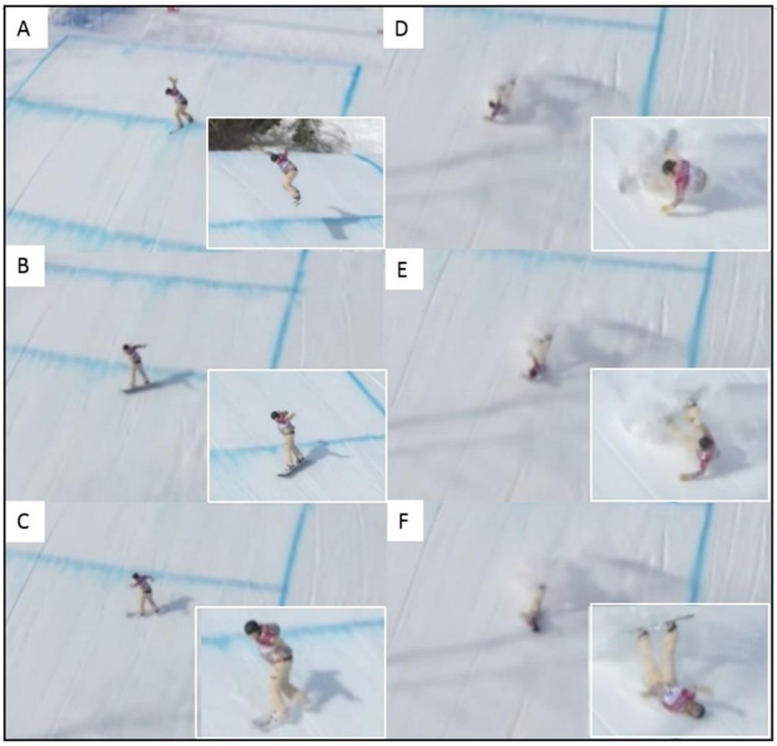

Figure 18. *Snowboard cross, typical example of a back-edge catch. Key crash events: A) The athlete is out of balance backwards and yawing during landing after a jump. B) She continues to yaw upon landing. Her bodyweight is first on the frontside edge of her snowboard. C) Her bodyweight shifts to the backside edge. The back edge catches the snow surface. D) She pitches backwards and impacts her buttocks, E) followed by her upper extremity and back, and F) and then impacts the back of her helmet (impact frame).*

Freestyle gross head injury mechanisms

Prior to the head impact situation, the majority of freestyle skiers were landing after a jump (n=10, 67%). The athlete fell or crashed in almost all cases (n=13, 87%). In two aerials cases the freestyle athletes did not fall or crash; however, the athlete's face impacted their own knee during a forward pitch during landing. The majority of freestyle athletes (n=13, 87%) made a personal technical or tactical mistake prior to crashing. In two ski cross cases (13%) the athletes made a forced error caused by opponent contact. Freestyle skiers primarily fell backwards (n=8, 53%), sideways (n= 3, 20%), forwards (n=1, 7%) or did not fall/crash (n=2, 13%) (Figure 19).

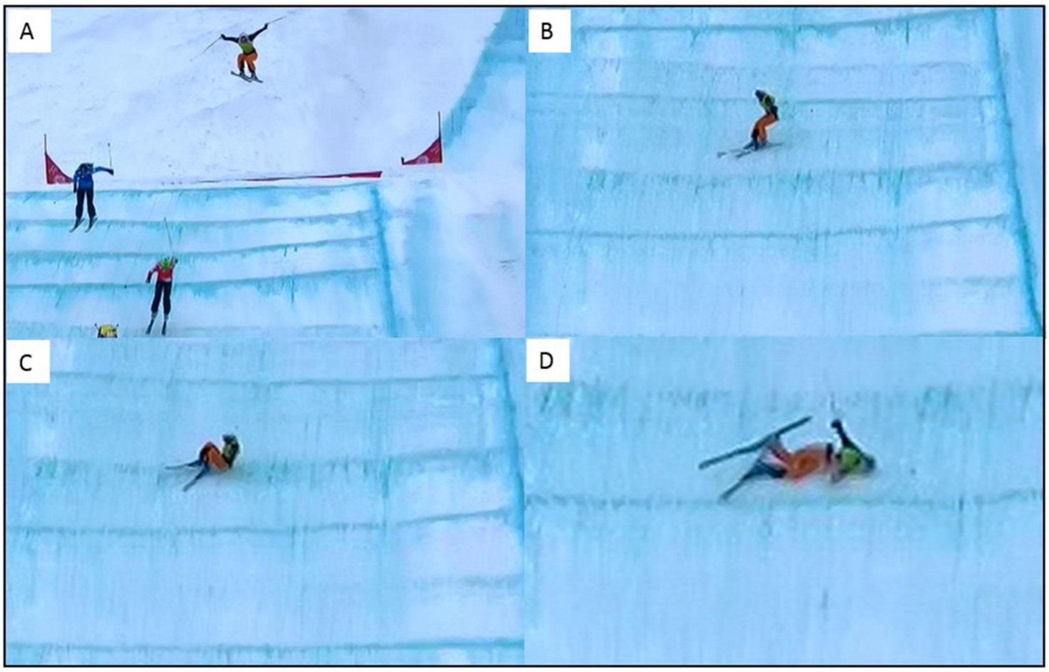

Figure 19. *Freestyle ski cross, typical example of a backwards pitching fall. Key crash events: A) Inappropriate course line and damping of jump. The athlete is out of balance backwards and yawing during the flight phase. B) The athlete lands on skis with skis partially across the slope. C) The athlete pitches backwards, impacting her buttocks. D) Rolls to the side and impacts the side of the helmet (impact frame).*

Backward pitching falls

We identified two previously described types of backward pitching falls among our freestyle and snowboarding cases: `slapback´ injuries and back-edge catches (Mecham et al., 1999, Fukuda et al., 2001, Koyama et al., 2011). Our systemetic video analysis revealed that the gross injury mechanism in 62% of our snowboarding cases was a back-edge catch, which is previously described as a common head injury mechanism in recreational snowboarders (Nakaguchi et al., 1999, Fukuda et al., 2001, Koyama et al., 2011, Nakaguchi and Tsutsumi, 2002). Previous studies have described that the most frequent causes of snowboarding head injuries are simple falls on slopes in beginners and falls during jumping in experts, while the most common injury mechanism is falling backwards, leading to an occipital impact (Nakaguchi et al., 1999, Fukuda et al., 2001, Koyama et al., 2011). We observed backward pitching falls frequently in alpine skiing, as well (35%) (Figure 20). Bailly et al. (2017) reported that falling backwards represented 14% of falls in recreational skiers, with the impact location being the occipital region in 73% of the backwards falls. Backwards pitching falls may therefore be more common among WC alpine skiers compared to in recreational skiers.

Sideways falls

We identified that for alpine skiers, sideways falls were the most common (45%) (Figure 20). Two common patterns were observed. The athletes were either mainly out of balance in the frontal plane (roll) in air during flight, falling to the left or right hand side, impacting the side of the helmet, or the athletes landed mainly out of balance in the transverse plane (yaw) after flight, subsequently catching the ski edge and tripping. Being tripped, the athlete then fell sideways, also impacting the side of the helmet.

Our findings are slightly contradictory to a recent study investigating head injury mechanisms in recreational skiers and snowboarders, where hospital data were combined with a survey based on sketches depicting the crash and impact locations (Bailly et al., 2017). Bailly et al. (2017) reported that "falling head first" while skiing was the most common injury mechanism (28%), followed by "falling sideways (catching the ski edge)" representing 19% of skiers` falls. The two main head impact locations were the frontal (57%) and facial (41%) areas (Bailly et al., 2017). However, for the sideways falls, they reported that 28% of head impacts were to the occipital region, which is similar to our findings (Bailly et al., 2017). This indicates that mechanisms of falling may be somewhat different between recreational and WC skiers, with recreational skiers having more impacts to the front/face and falling head first, although catching the ski edge and falling sideways has been identified as a common injury mechanism at both levels.

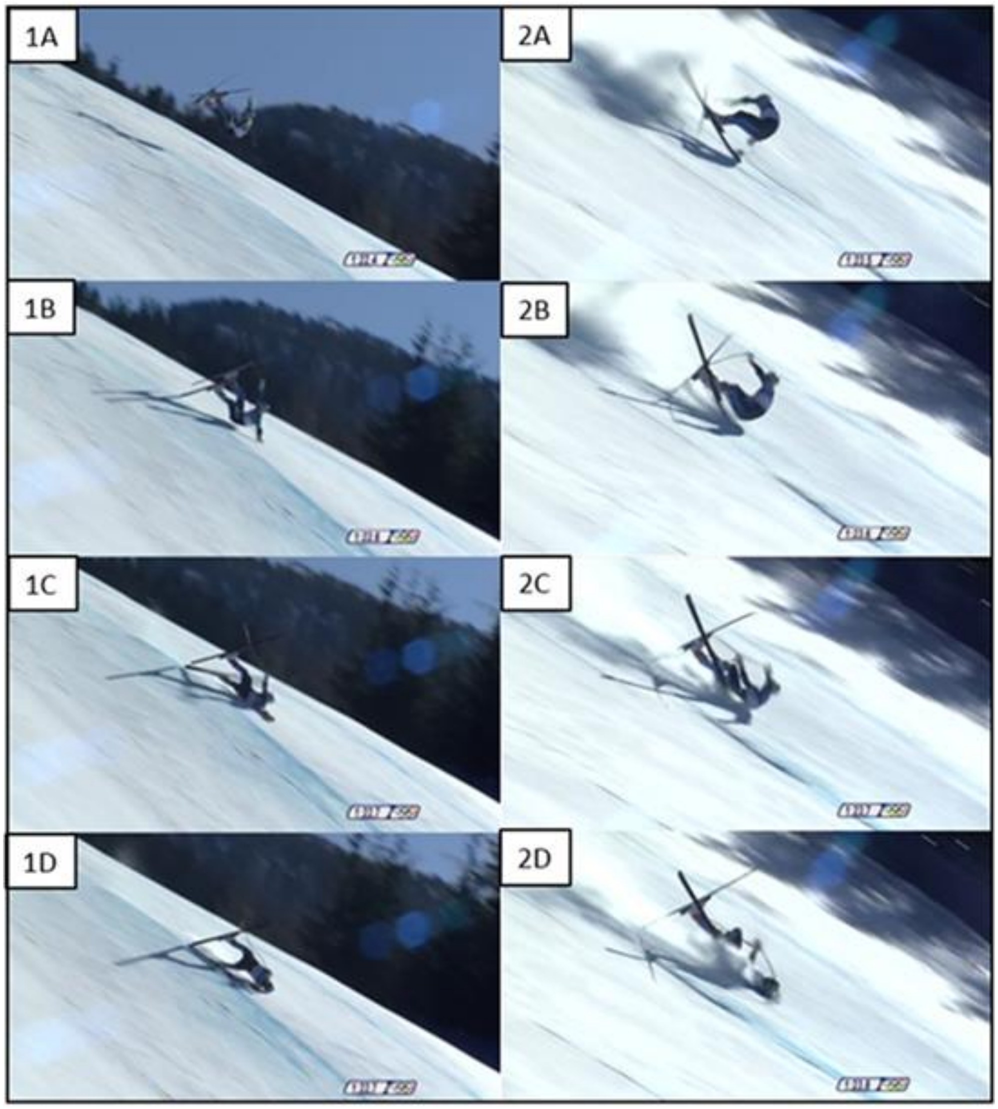

Figure 20. *Illustrating an alpine skier with two head impacts, and sideways and backwards pitching falls. Key crash events, impact 1: 1A-D) the athlete pitches backwards and rolls sideward to the left on impact with the snow. Key crash events, impact 2: 2A-D) the athlete pitches backwards and rolls on impact with the snow.*

Head impact injury reconstruction from broadcast video (Papers III and IV)

Description of analysed cases

We were able to analyse two snowboarding, two freestyle skiing and seven alpine skiing cases (Table 8.) In *Paper III*, all cases had one head impact, whereas in *Paper IV*, two cases (Case 2, Case 6) had two head impacts. In total therefore, we could analyse 13 head impacts from 11 cases. Only Case 7 of *Paper IV* complied with the new FIS helmet-testing rule at the time of injury.

Table 8. *Description of the analysed cases of Papers III and IV.*

		Sex	**Diagnosis**	**Severity (absence)**	**Season of injury**	**Discipline**	**Competition**
Paper III	Case 1	Male	Concussion	4-7 days	2012/13	Ski halfpipe	World Cup competition
	Case 2	Male	Concussion	4-7 days	2007/08	Ski cross	World Cup competition
	Case 3	Female	Concussion	8-28 days	2010/11	Snowboard cross	World Cup competition
	Case 4	Female	Concussion	0	2013/14	Snowboard slopestyle	Olympic Winter Games
Paper IV	Case 1	Male	Concussion	8-28 days	2009/10	Super-G	Olympic Winter Games
	Case 2	Female	Concussion	4-7 days	2009/10	Downhill	Olympic Winter Games
	Case 3	Male	ACL-injury, Concussion	>28 days	2008/09	Super-G	World Cup
	Case 4	Male	Concussion	4-7 days	2008/09	Downhill	World Cup
	Case 5	Female	Concussion	>28 days	2006/07	Downhill	World Cup
	Case 6	Female	Concussion	4-7 days	2007/08	Downhill	World Cup
	Case 7	Male	Concussion	>28 days	2014/15*	Super-G	World Cup

**Complied with new FIS helmet rule at time of injury (ASTM F2040 (Class A) and EN1077 and additional EN1077 test of 6.8 $m \cdot s^{-1}$).*

Linear kinematics

We found that in 11 of the 13 head impacts analysed, the estimated normal-to-slope preimpact velocity was greater than the prevailing minimum requirements at the time of the incidents of 5.4 m/s (EN 1077), 6.2 m/s (ASTM F2040), and the current FIS helmet rule of EN 1077 plus ASTM F2040 plus 6.8 m/s impact test for alpine giant slalom, super-G and downhill, and freestyle ski cross (mean 8.3 ± 2.6 m/s , range 1.9 ±0.8 m/s to 12.1 ±0.4 m/s (Figure 21). One alpine head impact had a normal-to-slope preimpact velocity below the previous FIS helmet-testing rule of 5.4 m/s (Figure 21). The change in head velocity during impact in the normal-to-slope direction ranged from 5.2 ± 1.1 m/s to 13.5 ± 1.3 m/s for the 13 impacts (mean 9.6 ± 2.3 m/s) (Figure 21).

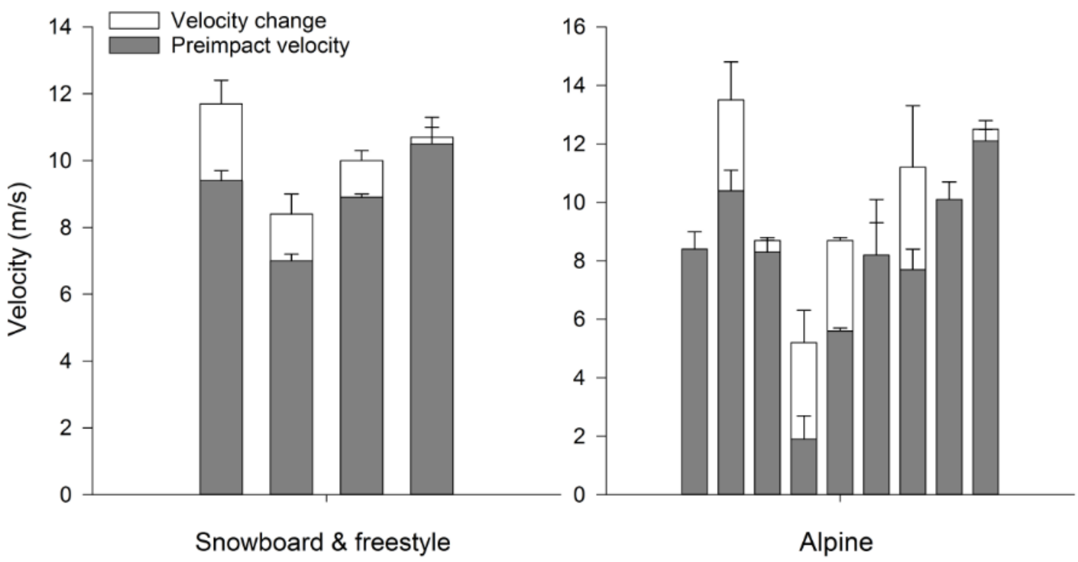

Figure 21*. Preimpact velocity and velocity change of the 13 analysed head impacts. The grey bars indicate the normal-to-slope preimpact velocity and the white bars display the linear velocity change (m/s) ±SD of the three trials of all 13 analysed head impacts in Papers III and IV. In two alpine cases there was a negative post-impact velocity, and in one alpine case the postimpact velocity was 0 ±0.9 m/s . This is illustrated by no visible velocity change in this graph (no visible white bar).*

Previous reconstructive studies of head impact kinematics in snow sports have reported similar results to our findings, with normal-to slope head impact velocities of 8.11 m/s, 7.8 ± 1.7 m/s and 11 m/s (Bailly et al., 2016, Yamazaki et al., 2015, Richards et al., 2008).

We do not know the head accelerations in our cases. Therefore, it is difficult to compare our findings to acceleration measures from head impacts in other sports. Still, the head impact velocity changes we found in our cases are comparable to velocity changes in American football (range 7.2 to 9.3 m/s), where also corresponding peak linear accelerations (range 64g to 112g) and angular accelerations (range 4253 to 8022 rad/s) have been reported (Viano et al., 2007, Pellman et al., 2003b, Beckwith et al., 2013). The velocity changes we reported are also similar to concussive head impacts in unhelmeted Australian football and rugby players, where the linear peak velocity change ranged from 3.2 to 9.3 m/s (Frechede and McIntosh, 2009).

Our results however, do not represent sufficient evidence to require a change in the helmet impact speeds in FIS mandated helmet rules in alpine and freestyle skiing and snowboarding. This is because we lack information about the relationship between real-world head impacts onto snow and ice, and laboratory head impacts during helmet testing procedures. In addition, our studies are limited by the sample size and a lack of information concerning the helmet models used.

An impact anvil is typically rigid, which will produce a greater head acceleration compared to a real-world impact against a compliant surface such as snow/ice. Headforms used in laboratory tests are also rigid and will produce a higher head acceleration compared to a human head or equivalent headform (Yamazaki et al., 2015). For those reasons, when considering equivalence between real world impacts and laboratory tests, laboratory helmet testing velocities on rigid anvils are often lower than what is observed in real-world impacts (Yamazaki et al., 2015). To fully understand our results therefore, future studies should perform helmet testing outdoors on real WC prepared snow, as this would help clarify the relationship between helmet testing on rigid anvils and real head impacts on a snow/ice surface.

Angular kinematics

The 9 freestyle, snowboard and alpine impacts where it was possible to measure angular velocity displayed sagittal plane peak helmet angular velocity immediately prior to impact (Figure 22). The mean angular velocity change of the 9 impacts was 40.2 ± 15.1 rad/s (range 21.2 ± 1.5 rad/s to 64.2 ±3.0 rad/s) (Figure 22).

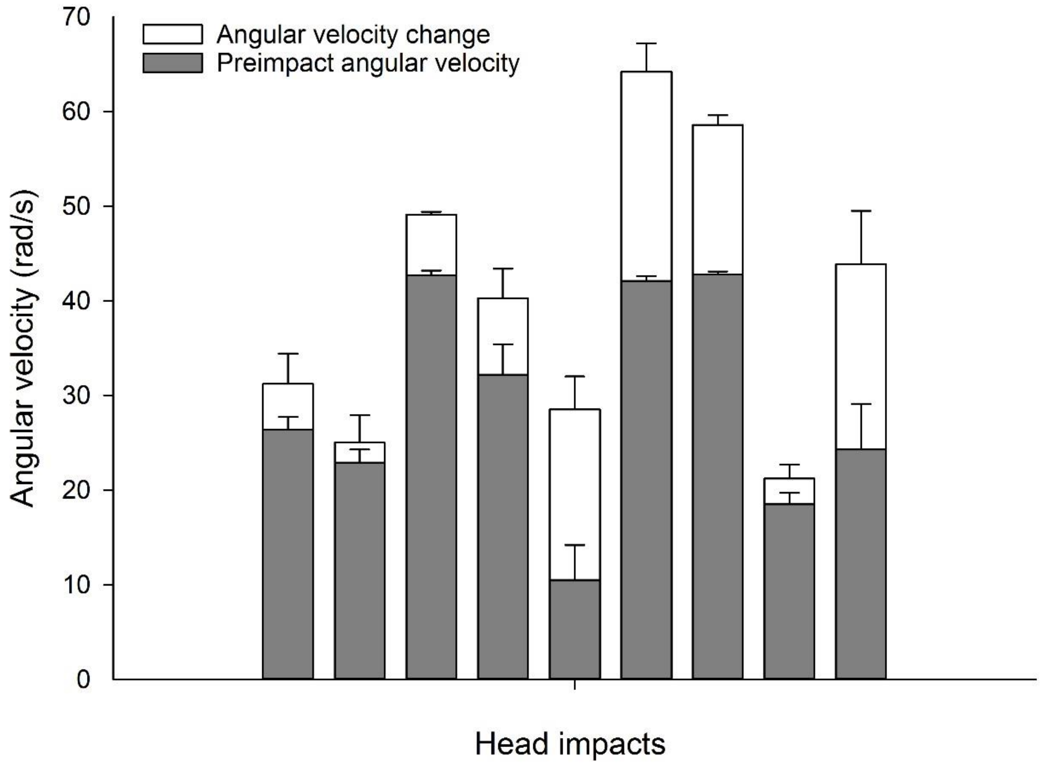

Figure 22. *The grey bars illustrate the preimpact sagittal plane head angular velocity (rad/s) ±SD for the three trials of cases 1 to 4 of Paper III and cases 1, 2, 4 and 7 (5 impacts) of Paper IV. The white bars display the sagittal plane head angular velocity change (rad/s) ±SD of the nine impacts.*

Our findings indicate that there is considerable change in the angular velocity of the head in each crash. It is important to consider the angular kinematics of the head in the causation of brain injuries (Gennarelli et al., 1982, Margulies and Thibault, 1992). The angular velocity changes we have reported are similar to results from other studies utilising laboratory reconstructions or mathematical models to replicate other injury situations.

Hajiaghamenar et al. (2015) investigated the response of female and male ATDs to describe the head impact kinematics and kinetics of different scenarios of falls onto a hard surface from standing. The head impact parameters were dependent on the fall direction and type, with backward falls without hip flexion being the most severe scenarios. The highest mean value of head peak translational acceleration (368 g for female and 451 g for male), impact force (14.7 kN for female and 22.8 kN for male), HIC_{15} value (2173 for female and 4142 for male) and peak angular velocity (48.7 rad/s for female and 58.9 rad/s for male) was observed for these backward falls (Hajiaghamemar et al., 2015). The peak angular velocity values reported by Hajiaghamenar et al. (2015) are similar to our highest measured angular velocity changes (maximum 64.2 ±3.0 rad/s, *Paper IV*). In backwards falls with hip flexion (which is more comparable to our crash situations), the ATDs obained mean head angular velocity of 32.7 ± 5.7, which is slightly lower than the mean angular velocity change (40.2 ± 15.1 rad/s, *Papers III and IV*) we reported (Hajiaghamemar et al., 2015).

In laboratory impact testing to different sites of an American football helmet and facemask, where the testing impact velocities ranged from 2.1 to 8.5 m/s, the resultant angular velocities measured by an accelerometre fitted mouthguard and a 50th percentage male ATD ranged between approximately 10 and 40 rad/s (Camarillo et al., 2013).

Elkin et al. (2016) used FE modelling to estimate the brain strains that develop during rear-end car crashes, to evaluate how these strains vary with different head kinematic parameters. Head kinematic data from 2 prior studies (one that focused on head restraint impacts in rear-end crash tests and another that focused on football helmet impacts) were used as input to the FE model. Brain strains correlated best with the head's angular velocity change for both impact conditions. The 4 crashes with head angular velocity changes greater than 30 rad/s generated the highest brain stains (Elkin et al., 2016).

Viano et al. (2007) studied the biomechanics of concussion in the struck player among 25 head impacts causing concussion in American professional football. The impacts were simulated in laboratory tests to determine collision mechanics. The impact response of the concussed player's head included peak accelerations of 94 ± 28 g and 6432 ± 1813 rad/s^2, and velocity changes of 7.2 ± 1.8 m/s and 34.8 ± 15.2 rad/s (Viano et al., 2007). The linear and angular velocity changes described during these concussive impacts are very smilar to the velocity changes we reported in *Papers III and IV*.

In comparison to helmet drop tests, in which pre-impact angular motion is minimal and angular motion during the impact is constrained by the test system, our results identified that, during the fall, the head had developed angular velocity preimpact and that there was a greater change in angular velocity during impact (Figure 23, Figure 24). Both our linear and angular velocity results (*Papers III and IV*) demonstrated that there was a rebound phase, which might not be anticipated in an impact with soft snow (Figure 23, Figure 24). The rebound motion of the helmet is indicated by a positive velocity post-impact, indicating an upwards movement of the helmet from the impact surface for the linear velocity, or a flexion movement of the head for the angular velocity. In 10 of 13 impacts, we measured a linear rebound motion up from the snow surface, and in all 9 impacts where we could measure angular velocity, we measured an angular rebound of the helmet. This change in head angular velocity would be reflected as head angular acceleration. The helmet and snow/ice impact interface may both contribute to rebound. Further research is therefore required on the snow/ice impact interface.

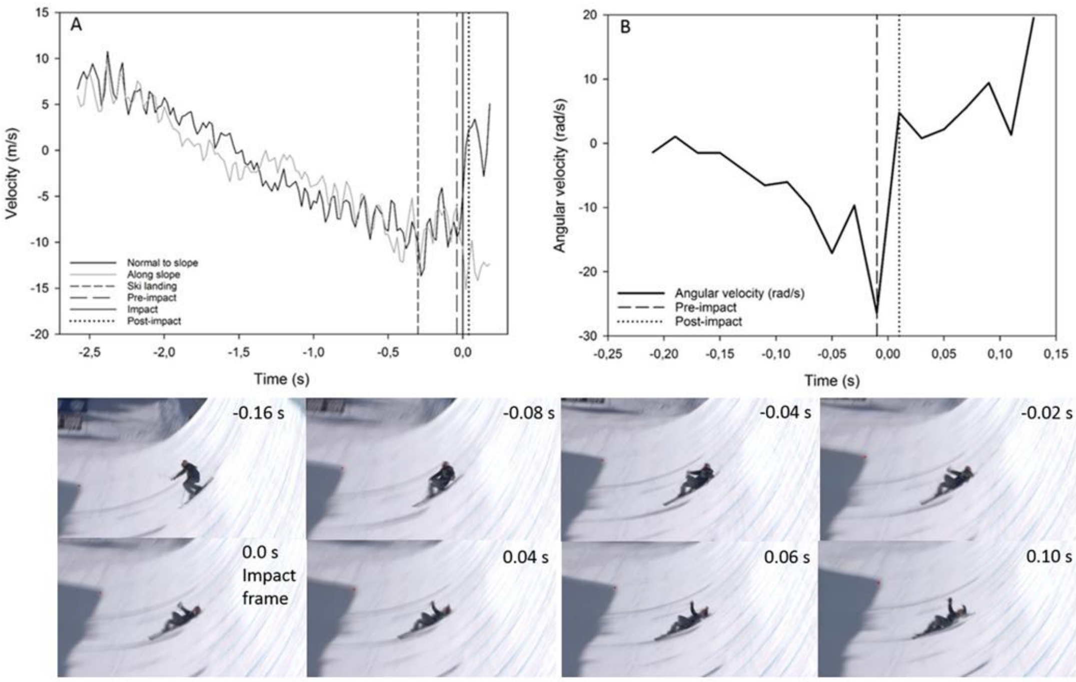

Figure 23. *From Case 1, Paper II (60Hz). Illustrating the linear (m/s) and angular (rad/s) velocity curves in relation to the time-sequence of the head impact injury situation, in a typical backwards pitching fall. There is a peak in angular velocity immediately preimpact, followed by a rebound motion, which results in a substantial change in angular velocity (panel B). Videos of all injury cases of Papers III and IV can be viewed as supplementary files to the papers at www.bjsm.bmj.com.*

Measurements of rebound on 150 motorcycle helmets in drop tests show that the coefficient of restitution varies by helmet model and drop height.(CRASH, 2017) The coefficient of restitution describes the relative elasticity of an impact; i.e. it governs the relationship between the relative velocities of two bodies before and after an impact (Hall, 2007). It is a unitless number between 0 and 1. The closer the coefficient of restitution is to 1, the more elastic is the impact. The closer the coefficient is to 0, the the more plastic is the impact. Algebraically, the relationship can be described as the following (Hall, 2007):

$$\text{Coefficient of restitution (e)} = \frac{\text{Relative velocity after collision}}{\text{Relative velocity before collision}}$$

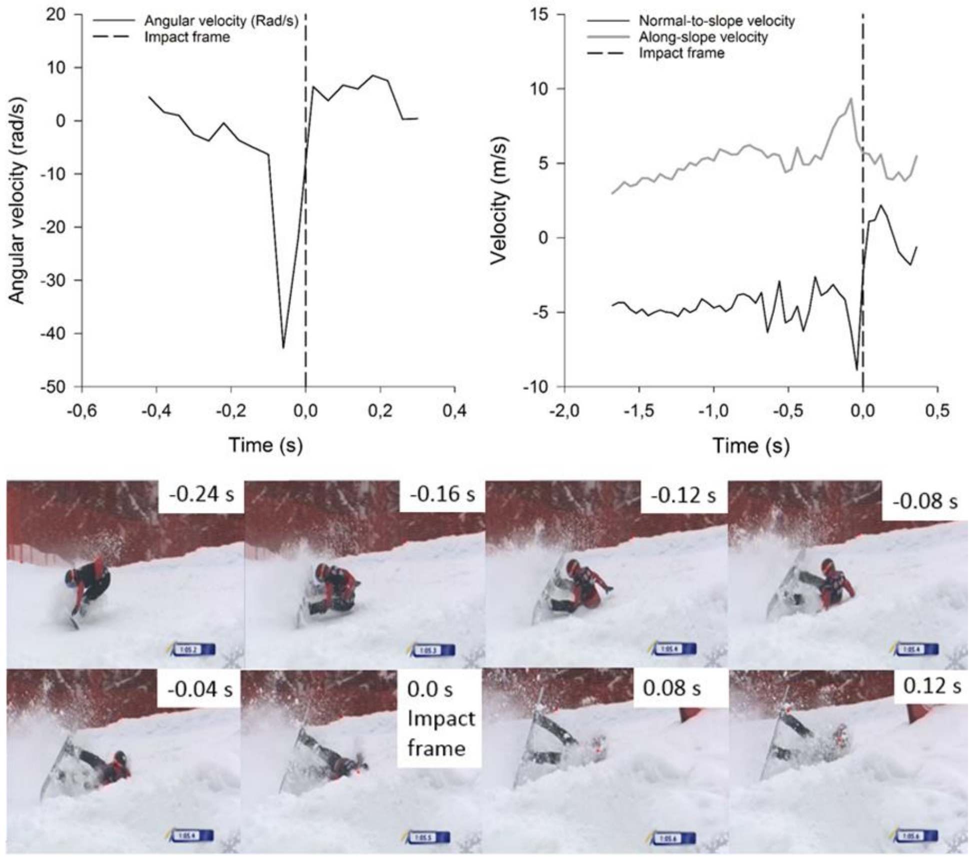

Figure 24. *From Paper III, Case 3 (25 Hz). Illustrating the linear (m/s) and angular (rad/s) velocity curves in relation to the time-sequence of the head impact injury situation, in a back-edge catch mechanisms, in a female snowboarder. There is a peak in sagittal plane angular velocity immediately preimpact, followed by a rebound motion of the helmet, which results in a substantial change in the angular velocity. Videos of all injury cases of Papers III and IV can be viewed as supplemetary files to the papers at www.bjsm.bmj.com.*

The average coefficient of restitution was 0.35 in 0.8 m drop tests compared to 0.27 in 2.5 m drop tests; where the mandated drop height in UNECE 22 (motorcycle helmets) is 2.5 m (CRASH, 2017). These results suggest that the selection of the foam liner properties is important and may be tuned to specific impact management requirements in standards. This issue might be addressed in a standard by (a) including performance criteria for the coefficient of restitution or (b) including an oblique impact test (McIntosh and Patton, 2015, McIntosh et al., 2013) to assess the ability of the helmet to manage the head's angular kinematics.

The impact angles of the helmet velocity vector relative to the slope at the frame of impact were between 6° and 78°. However, in our cases we do not have information about the snow properties, muscle activation (such as neck muscle contraction) or force transfer from the body or neck to the head at the impact, which makes it difficult to consider the consequence of the impact angles. Importantly, we also do not have information about angular velocity changes in other planes of movement. Yamazaki et al. (2015) described a frontal plane angular velocity change of 100 rad/s after a high speed sideways fall. In other words, angular velocity changes can be considerably greater than we have described, and may occur in all three planes.

Snow properties influence head impact biomechanics

Although a description of head impact velocities is essential to inform helmet testing standards, snow properties will influence peak head accelerations during a crash. Although FIS WC prepared snow is generally hard or icy, it is essential for future studies to investigate snow properties such as the liquid-water content, density and texture when reporting head impact magnitudes. In addition, the impact angle of the slope must be considered.

From previous laboratory head impact reconstructions with ATDs, we know that snow properties substantially influence the resultant head accelerations. Scher et al. (2006) reported that a helmet did not significantly alter head accelerations on soft snow, but significantly reduced head accelerations on hard snow. Similarly, Dressler et al. (2012) reported that helmets provided good head protection in hard snow impacts, reducing head accelerations by as much as 48 %. Head accelerations were low in soft snow impacts both with and without a helmet. Bailly et al. (2016) established that snow stiffness had a major contribution to the head impact metrics in their MADYMO reconstructions.

Scher et al. (2006) discussed that on impacts with icy snow surfaces, snow surface disruption was modest, highlighting the importance of energy dissipation through deformation of the helmet (i.e.

the foam liner). On soft snow, however, there was little likelihood of obtaining a severe head injury due to the energy dissipation associated with deformation and disruption of the snow surface in the area of head contact (Scher et al., 2006). In the soft snow impacts, there was significant disruption of the snow surface, which was manifested as compression and compaction of the snow at the head or helmet contact site, as well as surface redistribution, which meant the snow flew off the surface (Scher et al., 2006). This highlights the need for future helmet testing studies performing helmet testing outdoors on realistic WC snow conditions, and to quantify the snow properties during helmet testing.

Methodological considerations

Injury surveillance and medical information

All injury recording during the 7 WC seasons was through interviews with athletes, medical personnel or coaches. Recall bias is a challenge with retrospective interviews. However, a methodological study found that in the WC setting, retrospective interviews were the best method compared to prospective injury registration by team medical personnel or FIS Technical Delegates (Flørenes et al., 2011) Interview forms based on the race schedules were used to help the interviewee recall the date, location and circumstances of injury (Flørenes et al., 2011). Still, even if a recall bias may exist, we can not see any reason why this should be sex- or discipline-related and in that way influence our results regarding sex- or disciplines.

A greater problem could be that concussions are not recognised by athletes, coaches or medical personnel, and therefore are under-reported. Athletes might not self-report an injury they do not recognise as being harmful or dangerous at the time of competition (Greenwald et al., 2012). Although much focus has been given to concussion recognition through recent consensus conferences, we do not know what the uptake of new guidelines have been in the skiing and snowboarding medical community (McCrory et al., 2013a, McCrory et al., 2009, McCrory et al., 2017). From other sports it is known that concussions are considerably under-reported, with the most common reason in football being that the athlete did not think the injury was serious enough to warrant medical attention (Williamson and Goodman, 2006, McCrea et al., 2004).

The injury severity rating utilised in the FIS ISS is an operational injury definition typically used for injury surveillance in sports, and not a head injury specific severity rating. It would have been beneficial to have access to hospital records with standard head injury severity codes, such as

Abbreviated Injury Scale or Glasgow Coma Scale. However, this was not possible, and therefore certain limitations regarding the accuracy of the head/face injury data must be acknowledged.

When we split the head injuries into sub-categories, such as to investigate differences in head injury incidence between sub-disciplines, our ability to draw conclusions is restricted by the limited statistical power. This is due to the low number of head injury cases in each category.

Two recent literature reviews and two recent meta-analyses have documented that the use of helmets significantly reduces the risk of head injury, in addition to the severity of the injury, and does not increase the risk of neck injury among recreational skiers and snowboarders (Russell et al., 2010, Haider et al., 2012, Cusimano and Kwok, 2010, Hume et al., 2015). These reviews include case-control or prospective longitudinal studies that have investigated the effects of helmet wear vs controls or unhelmeted skiers/snowboarders. Helmet effectiveness cannot be evaluated in the same way at the WC level, as there are no un-helmeted controls. However, for instance in a biomechanical study evaluating helmet effectiveness in the FIS WC, one way of achieving control cases would be to compare impact characteristics of head injured athletes with athletes who received a head impact with no diagnosed injury. This would require that the uninjured athletes could provide a reliable account of receiving no injury. In WC athletes however, the FIS ISS monitors the season-to-season injury trends, so that it is possible to prospectively monitor if any changes, such as rule changes or changes to helmet testing standards have an effect on head injury incidence.

Video analysis and head impact injury reconstruction

During the systematic video analysis *(Paper II),* we could only obtain videos of 28% (13/47) and 36% (15/42) of snowboarding and freestyle skiing head and face injuries, respectively. This was mainly due to injuries not being videotaped by the television producer, or the injury situation was not visible on the video. In addition, many head and face injuries in snowboard and freestyle skiing occur during qualification runs, which are not broadcasted. Therefore, the data from freestyle skiing and snowboarding should be interpreted with caution. In *Paper III,* we could only obtain 4 snowboard and freestyle videos with a sagittal view of the crash. Nevertheless, our findings parallel previous epidemiological literature from the recreational level, and we therefore believe hat the injury mechanisms we have analysed are representative (Koyama et al., 2011, Nakaguchi and Tsutsumi, 2002).

In *Paper II*, we managed to acquire videos of 85% (29/34) of all WC alpine head and face injuries, ensuring that our sample of alpine injury videos was representative. Based on this, we can also confirm that the alpine cases we analysed in *Paper IV* are representative.

Error estimates

It was possible to perform separate digitizing trials of the pelvis during the flight phase for 5 cases in total in *Papers III and IV,* where we could estimate vertical and horizontal velocity and acceleration. In our analyses, we had to assume that the video footage was aligned with the true vertical axis, however, we cannot be certain about this. We partly verifed this by reporting the vertical acceleration and root mean square error during the flight phase. The root mean square error during the flight phase of 5 cases ranged between 0.47 to 1.55 m/s from the regression line, indicating a low error of our vertical velocity estimates in some cases, while the error was higher in others. Acceleration due to gravity is 9.81 m/s^2, and is therefore the target value for our vertical acceleration estimates. The vertical acceleration ranged from 8.7 m/s^2 to 10.7 m/s^2. Our target measure for the horizontal component of the gravitational acceleration is 0 m/s^2. The horizontal acceleration ranged from -0.2 m/s^2 to 2.7 m/s^2, and the root mean square error in the horizontal direction ranged from 0.8 m/s to 2.9 m/s from the regression line.

The estimated vertical acceleration during the flight phases of the elegible cases was close to the gravitational acceleration constant of 9.8 m/s^2, which indicates that the accuracy of our vertical velocity estimates was reasonable, while our horizontal error was greater. The relatively accurate results relating to the vertical acceleration measurements most likely arose because of the restrictive case inclusion and exclusion criteria. However, we do not know what is the likely cause of the discrepancy between the estimated acceleration due to gravity and the target value of 9.8 m/s^2. This could be due to discrepancies relating to the vertical axis of the camera, digitization error or calibration length error.

The mean root mean square error of the 3 digitizing trials of the helmet position in the normal-to-slope direction was 1.9 cm and 2.5 cm, and in the along-slope direction 1.7 cm and 3.0 cm, in *Papers III and IV* respectively. The mean root mean square error of the 3 trials of the angular measurement of the helmet was 3° in both *Papers III and IV*. These results indicate that the intrarater digitizing of the helmet and the angular measurement of the helmet was consistent between trials.

Video quality

In general, video quality and available camera views represent a challenge not only when determining the head impact frame but also when assessing the gross injury mechanisms. However, in *Paper II* the assessment was consistent across analysts. In *Paper II*, we included videos where the head impact frame was not visible. Nonetheless, we could still perform an accurate analysis of the gross body biomechanics leading up to the head injury, which provides novel and valuable information.

In *Papers III and IV,* there are additional concerns regarding the video quality. TV footage will typically become blurry when large velocity changes are present. Coupled with limited frame rate (25-60 Hz), this makes it challenging to estimate impact velocities accurately. However, our error assessments showed that the measurements were reasonably accurate. We attempted to optimize the accuracy by performing 3 trials for the linear velocity and angular velocity measures, and reporting the mean. The mean root mean square error of the digitized head position was under 3 cm, indicating that the intra-rater digitizing was consistent between trials.

Also the video resolution, the athlete`s pixel size in the video image as well as the visibility of landmarks in the background may influence the estimation of displacement-time data from videos. The main limitations in our velocity analyses, however, are not from the limited spatial resolution, but from snow spray, camera blur and limited temporal resolution. Blur is mainly a problem in the few frames immediately after impact. Hence, it was not possible to accurately measure the kinematics during the short duration of the impact. Image quality until the last frame before impact allowed for accurate visualisation of helmet reference points and estimation of head velocity immediately before impact, as verified by the estimates of vertical acceleration during flight.

Robustness of methods

To test the robustness of our methods of *Papers III and IV*, we collaborated with a research group specialising in neuronic engineering, from Kungliga Tekniska Högskolan (KTH), in Stockholm, Sweden. The aim was for the research group from KTH to use information from our 2D motion analysis for further studies, initially for rigid body modelling with MADYMO software. The first step of this process consisted of one reseracher from KTH performing two different video analysis techniques to analyse the 4 cases of *Paper III.* The two techniques consisted of:

1. A similar approach as ours, but with different reference points (both in the foreground of the athlete as well as in the background of the athlete)
2. A methodology based on a 3D model-based image-matching technique. However, this model could only estimate velocity perpendicular to the ground. Both methods produced very similar results (less than 10% difference in estimated maximal velocities) (Figure 25).

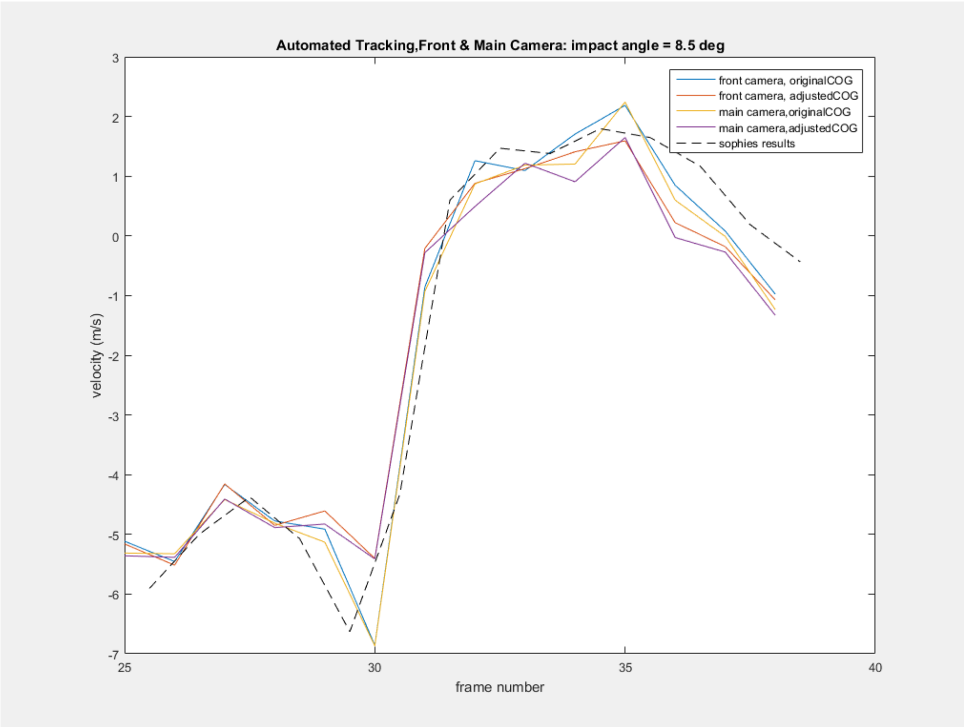

Figure 25. *Comparison of digitizing trials with the SkillSpector software by the principal investigator and a method using the MBIM technique by a different researcher. The principal investigator`s trial is depicted in the black dotted line. The different coloured lines represent the trials conducted by a different researcher using a 3D image matching software (Personal communication, reproduced with permission from Vanessa Thomson 24.11.17).*

To filter the linear velocity, we chose a 15 Hz cut-off frequency because lower frequencies would over-smooth the peak velocity estimate. Through different filtering trials, we identified that a 7 Hz cut-off could underestimate the velocity change of the impact by approximately 28%

compared to a 15 Hz cut-off. On average, the 15Hz spline filter peak velocities estimates differed from those of simple differentiation by only 3% (Figure 26).

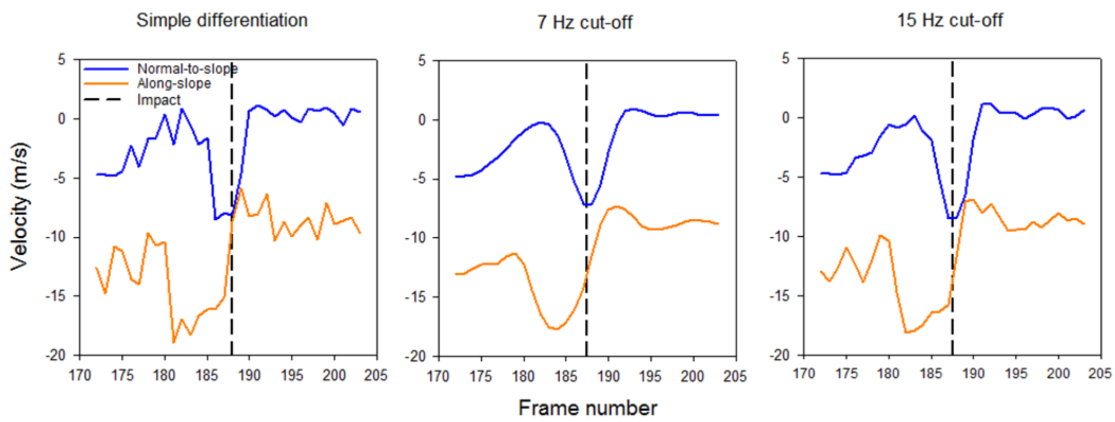

Figure 26. *An example of different filtering trials with simple numerical differentiation compared to a smoothing spline using 7 Hz and 15 Hz cut-off frequencies in Case 4, Paper III.*

We chose not to filter the angular velocity signal, considering that this would give the most realistic estimate of the true angular velocity change. Although we could have used an algorithm including more time points to estimate velocity (e.g. a Butterworth or spline filter), we chose to use a simple differentiation scheme because there were large changes in head orientation between frames, which progressed towards head impact (up to 40° differences between two frames). Therefore, due to the limited temporal resolution, and with a root mean square error of only 3°, we would argue that a simple differentiation scheme will likely provide the best estimates of the true velocities, since other methods would smooth the signal and hence likely underestimate the maximal velocity immediately prior to the impact. Small measurement errors could potentially generate large errors in the estimates, but the angular velocity curves, showing a steady increase in angular velocity towards impact indicate that our estimates are realistic.
However, some caution and interpretation is required if these angular velocity change estimates were to be compared with angular velocity measured in controlled experiments using defined signal conditioning methods.

As previously discussed, 2D motion analysis software requires movements to be in a pre-selected movement plane. It has acceptable results for essentially planar movements but it ignores movements out of the chosen plane. We cannot quantify the degree of out of plane movement from the sagittal view in our videos. We can estimate though, that a 10° offset would result in 2% error (Sin(80)), 20°offset would result in 6% error (Sin(70)) and 30° offset would result in 13% error (Sin (60). If we assume less than 25° error in camera angle, this would mean less than 10% error in our velocity estimates. We have for this reason chosen to show the image sequences of the athlete movement pre-impact and at the frame of impact, so that it is possible for the reader to see the actual camera view and to assess whether there is any discrepancy from the sagittal view. Most important however, are the estimates of vertical and horizontal accelerations, which suggest that our velocity estimates are reasonable.

Implications for injury prevention

The FIS ISS was developed prior to the 2006/07 winter season as an initiative to increase attention to athlete safety and injury prevention, with the ultimate objective of reducing the risk of injuries among the athletes by suggesting preventive measures for the future. One part of this overall research objective has been to understand the causes of injury, focusing on the injury mechanisms, and the contribution of course design and safety equipment. Knowledge about injury mechanisms can provide important information about how rules and regulations, as well as athlete behaviour, can contribute to reduce the risk of injury and avoid high-risk situations (Bahr and Krosshaug, 2005). In alpine skiing for example, athletes must ski as efficiently as possible, as performance is determined by the racing time measured to a hundredth of a second, but at the same time they have to adapt their speed and trajectory to their technical skills and manage risk responsibly (Bere and Bahr, 2014). Injury causes are most often multifactorial and complex, which means that to identify the most critical factors, a combination of different methodological approaches is useful (Krosshaug et al., 2005). In this project, we have conducted an epidemiological study to gain knowledge about the incidence of head injuries, a qualitative video analysis to describe gross head impact injury mechanisms, and two quantitative video analyses to estimate gross head impact biomechanics. Through this research, we have identified some key areas to address, which may help increase athlete safety.

Investigating the epidemiology of head injuries among WC athletes revealed that while concussion is the most common diagnosis, future prevention strategies should continue to address severe head injuries across all disciplines, promote adequate recognition and medical attention of all head injuries, and target freestyle and snowboarding athletes, with at least equal attention given to female athletes as to males.

Based on the three helmet ejections (10% of cases) we observed in alpine skiing, it is important to ensure that FIS WC athletes have optimally fitting helmets, which are fastened correctly, as this could potentially be an area of improvement with respect to athlete safety. Many athletes experienced two or more head impacts, which may be an important consideration for helmet manufacturers with respect to helmet design and construction. Our observation that the helmet continues moving post-impact, combined with findings from *Papers III and IV* where we identified a linear and angular rebound motion up from the snow surface postimpact could be an important consideration for helmet manufacturers. Both the helmet and the snow impact surface will influence rebound, and future helmet standards could potentially address these issues.

In snowboarding and freestyle skiing, most head injuries occurred during landing from a jump, or when crashing while passing an element. The primary focus for course design in snowboard and freestyle skiing should therefore be on safe jump and landing constructions, and on the design of elements, such as banked turns. Future studies should investigate whether and how course elements affect injury risk. How the placement and spacing between elements, the combination of elements and the width of the course affect the risk of injury should be investigated further.

In our systematic video analysis *(Paper II)*, we identified that across all disciplines, the majority of crashes occurred due to personal technical or tactical mistakes. However, in 7/28 (25%) of freestyle and snowboard cases, we identified that the head injury situations were caused by forced errors due to contact between athletes. From previous epidemiological research, we know that the injury incidence was significantly higher in final runs (in heat formats) compared with individual qualification runs in snowboard cross for males (Steenstrup et al., 2011). It has been assumed that more injuries happen in final runs because of external risk factors such as space constraints in the course and competition between athletes for the ideal line (Steenstrup et al., 2011). In WC Snowboard cross riders, the main mechanisms of injuries were falling at an obstacle (52%) and collisions with competitors (44%) (Torjussen and Bahr, 2006). As we identified in *Paper II*, although intentional contact is prohibited by the FIS rules of contact (www.fis-ski.com), athletes occasionally are in intentional or unintentional contact with each other during heats, which does influence the risk of injury.

Similarly, in video analyses of injury situations in general among WC ski and snowboard cross athletes, the primary causes of the injuries were a technical error at take-off resulting in a too high jump and subsequent flat-landing, or unintentional skier–opponent contact in jumping, bank turning and roller situations (Randjelovic et al., 2014, Bakken et al., 2011). Randjelovic et al. (2014) therefore discussed that attention should be directed at the jumping and landing areas in relation to the jump profile, course width at take-off and, most importantly, the landing area. Further, they suggested that a reduction of the number of skiers in each heat could potentially reduce some stress factors that possibly contribute to the personal mistakes frequently observed, but this would represent a radical change to the nature of the sport (Randjelovic et al., 2014).

Most of our analysed alpine head impact injury cases came from the speed disciplines (downhill and super-G). In alpine skiing, safe course design in general must be a priority. Gilgien et al.

(2014) reported that in fall or crash situations, the magnitude of speed is of particular importance since speed determines the kinetic energy that has to be dissipated during a crash impact. In technically demanding sections such as jumps, rough terrain and turns, anticipation and adaptation time decreases with speed and mistakes might be more likely to occur (Gilgien et al., 2014). Further investigations into the reasons athletes make mistakes during turning, and into the causes of inappropriate gate contact, are warranted, in addition to addressing jump and course safety. It seems reasonable to suggest that reducing skier speeds during turns and terrain transitions, and focusing on optimal safety jump design would contribute to reducing injury risk.

Considering that we identified that over 40% of the alpine skiers had inappropriate gate contact, which threw the skier out of balance and ultimately led to the crash, further research into the optimal design of release gate panels and poles should continue.

In 11 of 13 head impacts reconstructed from broadcast video, the preimpact velocity was higher than the current strictest FIS helmet testing rule of 6.8 m/s. Considering this, helmets offered a high level of protection to the head in freeestyle skiing and snowboarding, however, in alpine skiing there were two severe concussions among 7 analysed cases. Nevertheless, as we do not have information about the snow properties in these incidents, it is not possible to relate our findings to laboratory helmet testing standards. We identified that the head underwent a considerable angular velocity change during the head impact combined with a rebound motion, which may contribute to brain injury. The influence of the snow impact surface and the helmet foam liner characteristics requires further research in order to optimise helmet performance and athlete protection. Future laboratory or field-based studies should therefore examine snow properties quantitatively and perform helmet impact tests on real-life snow and ice.

Conclusions

I. The majority of head/face injuries were nervous system injuries/concussions (81.6%) and one in four injuries was severe. Freestyle skiers had the highest overall head injury incidence. Across all disciplines, the injury incidence was somewhat greater in women than in men.

II. Head/face injuries mostly occurred while turning, landing from a jump or when passing elements. Most falls were backwards pitching and sideways falls, with a common crash sequence of impacting the snow surface with the skis or board first, followed by the upper or lower extremities, buttocks/pelvis, back and finally the head in 84% of cases. Impacts to the rear and side of the helmet dominated, and most athletes experienced one or two head impacts. In alpine skiing, the high number of injuries occurring due to inappropriate gate contact, and the proportion of helmet ejections observed represent a concern.

III. In 11 of 13 head impact injury cases reconstructed from broadcast video, the estimated normal-to-slope preimpact velocity was greater than the prevailing helmet rule at the time of injury and higher than the current strictest FIS helmet rule of 6.8 m/s. However, we do not have information about the snow properties in these incidents, which makes it impossible to relate our findings to laboratory helmet testing standards. The head underwent a substantial angular velocity change during the head impact combined with a rebound motion, which may contribute to brain injury.

Future research

Although the present studies have provided important information about head injuries in alpine and freestyle skiers and snowboarders, further research is needed:

1. Female athletes had a somewhat higher incidence of head injuries. Injury surveillance should continue so that the injury incidence in both sexes can be monitored also in the future. For instance, should FIS or the IOC implement rule changes with the aim of reducing injury risk in e.g. females (such as having separate courses, or providing jump options), continued injury surveillance will be essential to detect effects of these interventions.
2. Continued injury surveillance is essential to monitor if the new FIS helmet rule implemented in 2013/14 has had an effect on head injury risk in downhill, super-G, giant slalom and ski cross. A specific suggestion for future research is to utilise FIS ISS data to investigate the head injury incidence for the eligible disciplines before vs after the implementation of the new helmet rule, as was done in alpine skiing when new ski regulations were implemented (Haaland et al., 2016). In addition, the disciplines where the new helmet rule has not been implemented should be monitored for developments in head injury incidence and severity.
3. Freestyle athletes had the highest head injury risk and prior to the head impact situation, 67% of freestyle skiers were landing after a jump. Research into optimal course design, inrun speed, jump construction and landing design is essential if freestyle skiing safety is to be addressed.
4. Through reconstruction of head impact injury cases from broadcast video, we identified a useful method for studying gross injury mechanisms and head/helmet kinematics. However, these studies now need to be reproduced on larger samples.
5. We observed that there is a linear and angular rebound motion of the helmet up from the snow surface postimpact. To develop helmets that minimise rebound motions up from a snow surface, further research into snow properties and helmet foam liner properties is needed.

6. To increase our understanding of the differences between real-world impacts on snow and laboratory impacts, the logical next step for further research following our head impact injury reconstructions, is to perform helmet testing outside on real WC prepared snow.

8. A potential "whipping" head injury mechanism in snowboarding, as suggested by Richards et al. 2008, could be further investigated by realistically reconstructing the crash sequence we have described for snowboarding back-edge catches: edge catch, extremities, buttocks/pelvis, back and lastly the head. A potential "whipping" mechanism in freestyle and alpine skiing could also be investigated based on the crash sequences we have described.

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Papers I to IV

Head injuries among FIS World Cup alpine and freestyle skiers and snowboarders: a 7-year cohort study

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ABSTRACT

Background Traumatic brain injury is the leading cause of death for skiers and snowboarders. Fatal head injuries have also occurred at the International Ski Federation (FIS) World Cup (WC) level. We therefore wanted to describe the risk of head injuries across disciplines and sex among WC skiers and snowboarders.
Method We conducted retrospective interviews with FIS WC athletes at the end of seven consecutive seasons (2006–2013) to register injuries sustained during the competitive season. Head injuries were classified as 'head/face' injuries and did not include neck or cervical spine injuries. To calculate the exposure, we extracted data from the official FIS website for all WC competitions for each of the athletes interviewed.
Results A total of 2080 injuries were reported during seven WC seasons. Of these, 245 (11.8%) were head/face injuries. Of the 245 head/face injuries reported, nervous system injuries/concussions were the most common (81.6%) and 58 of these were severe (23.7%). The injury incidence per 1000 competition runs was higher in freestyle (1.8, 95% CI 1.2 to 2.4) than in alpine skiing (0.9, 95% CI 0.6 to 1.2; risk ratio (RR) 2.05, 95% CI 1.25 to 3.46) and snowboard (1.0, 95% CI 0.6 to 1.3; RR 1.85, 95% CI 1.15 to 2.99). Women had a higher injury incidence (5.8, 95% CI 4.8 to 6.9) versus men (3.9, 95% CI 3.2 to 4.6; RR 1.48, 95% CI 1.15 to 1.90) throughout the season (per 100 athletes).
Conclusions The majority of head/face injuries were nervous system injuries/concussions and one in four injuries was severe. Freestyle skiers had the highest overall head injury incidence. Across all disciplines, the injury incidence was higher in women than in men.

INTRODUCTION

At the International Ski Federation (FIS) World Cup (WC) level, the rate of head injuries in alpine skiing, freestyle skiing and snowboarding has been reported to range between 10% and 13.4%.[1–3] Data from the recreational level report that traumatic brain injury is the leading cause of death and catastrophic injury for skiers and snowboarders.[4] Two fatal head injuries have occurred at the FIS WC level in recent years. It is therefore of interest to investigate the risk of head injuries among WC skiers and snowboarders, with the long-term goal of preventing head injuries in this setting.

Jumping and falling have been reported as potential risk factors for head injuries in recreational skiers and snowboarders.[5–7] Recent studies found that head injury and concussion risk were increased in terrain parks, which consist primarily of aerial elements, compared with on traditional ski slopes, and that the odds of head/neck injury were greater on aerial features in a terrain park.[5 6] The WC includes disciplines with aerial elements (alpine downhill and super-G, ski cross and snowboard cross, half pipe, big air, aerials, slopestyle and moguls) and disciplines without aerial elements (alpine slalom and giant slalom, snowboard parallel slalom and parallel giant slalom). So far, we do not know whether aerial disciplines have the highest injury risk at the WC level.

A higher incidence of concussion has been reported among female athletes than among male athletes in sports with similar actions, rules and equipment.[8–10] Men and women compete in the same courses in snowboarding and freestyle skiing, whereas in alpine skiing men and women have separate race circuits. Comparing sex differences in a population where the competition conditions are similar (snowboard and freestyle) and different (alpine), can give us valuable insight into how this could affect injury risk, which is important in order to prevent injuries.

The aim of this study was therefore to investigate the incidence of head injuries, including the severity and the types of injuries, in the different alpine, freestyle and snowboarding disciplines, in addition to examining any sex differences in head injury risk.

MATERIALS AND METHODS

Study design and population

We recorded injuries through the FIS Injury Surveillance System (ISS)[11] based on annual retrospective athlete interviews during seven WC seasons (2006–2013).

Athletes on the WC teams from the USA, Austria, Canada, Finland, France, Germany, Italy, Switzerland, Norway and Sweden were interviewed at the WC finals at the end of each of the seven seasons. During the study period, we also included athletes from several other teams to increase the study population. The WC season was defined as starting at the first WC competition of the season (usually October/November) and ending at the last WC competition of the season (usually at the end of March), resulting in a 5-month to 6-month WC season. If an athlete was not present at the event, due to injury or other reason, or if the athlete did not understand English, the team coach, physician or physiotherapist was interviewed. The team had to have a response rate of ≥80% to be included. All athletes included were registered in the FIS database, had started in at least one FIS WC competition and had to be confirmed by the team

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coach as a member of the official WC team. The team coaches reviewed our lists of athletes to confirm which athletes belonged to the official WC team and added athletes if any were missing from our lists.

All interviews were conducted in person by physicians or physiotherapists from the Oslo Sports Trauma Research Center in the finishing area, after team captains' meetings or during organised meetings at the competitors' hotels. We completed a standardised interview form for each athlete, where the athlete consented to participate in the FIS ISS.[11]

Injury registration

If the athlete reported an injury, a specific injury form was also completed for each injury.[11] We defined injuries as "all acute injuries that occurred during training or competition and required attention by medical personnel."[12] The injury form included information about the date and place of injury, injury circumstances, body part injured, side (left/right), injury type, injury severity and the specific diagnosis. The injury definition and the classification of injury information was based on a consensus document on injury surveillance in football.[12] Head injuries were classified as 'head/face' injuries and did not include neck or cervical spine injuries. Injury type was classified as fractures and bone stress, joint (non-bone) and ligament, muscle and tendon, contusions, lacerations and skin lesions, nervous system including concussion, other injury or no information available. We also recorded the specific diagnosis, and for all head/face injuries classified as 'nervous system injuries including concussion', the diagnosis was 'concussion'. Injury severity was classified according to the duration of absence from training and competition as follows: slight (no absence), minimal (1–3 days), mild (4–7 days), moderate (8–28 days) and severe (>28 days).[12]

Exposure registration

To calculate exposure, we obtained the exact number of started runs by each of the athletes interviewed from the official FIS competition website (http://www.fis-ski.com) for each of the seven seasons (2006–2013). The result lists for each of the WC, World Ski/Snowboard Championships (WSC) and Olympic Winter Games (OWG) competitions during the seven seasons were extracted one by one from the FIS website into an Excel file. Specific variables were added to the result for each of the athletes, that is, date, discipline, place and sex. In addition, we created a new variable to calculate the number of started runs for each athlete per competition. The exposure data were transferred to our database (Oracle Database 11 g, Oracle Corporation, California, USA) and linked to the injury data recorded through the interviews. We calculated total exposure, as well as exposure for men versus women and for each of the different snowboarding, freestyle and alpine subdisciplines.

Statistical analysis

The injury rate was expressed as the absolute injury rate (number of injuries per 100 athletes per season) and the relative injury rate (number of injuries per 1000 competition runs). When calculating the absolute injury rate, we included all recorded injuries during all training and competitions throughout the seasons, while we only included injuries in WC, WSC and OWG competitions when calculating the relative injury rate, as exposure data (the number of runs started) were only available for these events. The WC, WSC and OWG exposure calculation includes competition runs (qualification and final runs) only, not official training runs. Calculations were based on the Poisson model, and Z tests were used to compare the injury rate and injury pattern between groups. Injury incidences and risk ratios (RR) are presented with 95% CI, and a two-tailed p value of <0.05 was considered significant.

RESULTS

We interviewed 5247 snowboard, freestyle and alpine skiing athletes during the seven seasons (2006–2013), including 3203 men and 2044 women (table 1). The majority of interviews were conducted with the team coach (n=2954, 56.3%) or athlete (n=1843, 35.1%). In some cases, information was also obtained from doctor/technical delegate reports (n=325, 6.2%), from team physicians (n=19, 0.4%) and from team physiotherapists (n=106, 2%).

A total of 2080 injuries (749 in snowboard, 668 in freestyle, 663 in alpine) were reported during the seven WC seasons. Of these, 245 (11.8%) were head/face injuries (table 2). The most common injury type was classified as nervous system injuries/concussions (n=200, 81.6%), and of these, all were reported to us with a diagnosis of concussion.

Injury circumstances and severity

All head/face injuries occurred while skiing/riding on snow and 122 (49.8%) injuries took place during competitions. The 122 competition injuries included injuries occurring during non-FIS competitions such as, for example, the X-Games or Dew Tour. Of the 122 competition injuries, a total of 96 head/face injuries (39.2%) took place during WC, WSC and OWG competitions. Only the 96 WC, WSC and OWG injuries were included for further analyses of competition injuries, as exposure data were only available for these events. There were 118 (48.2%) training injuries. In five cases (2%), we did not have information about the circumstances of injury. Of all head/face injuries (n=245), 57 (23.3%) were moderate and 58 (23.7%) severe, leading to an absence from training or competition of 8–28 or >28 days, respectively.

Overall head/face injury incidence

The overall incidence (number of injuries per 100 athletes per season) of head/face injuries (n=245) was higher in freestyle (5.7, 95% CI 4.5 to 6.8) and snowboard (5.0, 95% CI 4.0 to 6.0) compared with alpine skiing (3.5, 95% CI 2.7 to 4.4; RR 1.61, 95% CI 1.17 to 2.22 vs freestyle; RR 1.43, 95% CI 1.04 to 1.96 vs snowboard).

The overall incidence of head/face injuries was higher for women compared with men (table 3). Freestyle and snowboard

Table 1 Number of athletes interviewed in International Ski Federation World Cup alpine skiing, freestyle skiing and snowboarding for each of the seven seasons (2006–2013) among males and females

	Snowboard		Freestyle		Alpine		
Season	Male	Female	Male	Female	Male	Female	Total
2006/2007	92	50	107	46	144	116	555
2007/2008	186	94	177	86	148	113	804
2008/2009	173	96	143	103	148	115	778
2009/2010	172	99	96	56	140	128	691
2010/2011	202	113	171	105	157	118	866
2011/2012	102	54	89	53	148	118	564
2012/2013	238	125	207	132	163	124	989
Total	1165	631	990	581	1048	832	5247

Table 2 Distribution of injury types for head/face injuries (n=245) reported during seven seasons (2006–2013) of the International Ski Federation World Cup, during competition and training, for snowboard, freestyle skiing and alpine skiing

		Head/face injury types						
Discipline	Sex	Nervous system including concussion	Laceration/skin lesion	Fractures/bone stress	Contusions	Muscle and tendon	Other	Total (n)
Snowboard	Males	40	1	0	0	1	0	42
	Females	39	3	1	5	0	0	48
	Total	79	4	1	5	1	0	90
Freestyle	Males	41	2	1	1	0	1	46
	Females	35	2	4	0	0	2	43
	Total	76	4	5	1	0	3	89
Alpine	Males	27	4	3	2	0	0	36
	Females	18	7	2	1	0	2	30
	Total	45	11	5	3	0	2	66
Total (n, %)		200 (81.6)	19 (7.8)	11 (4.5)	9 (3.7)	1 (0.4)	5 (2.0)	245

women had a higher injury incidence compared with men, while no sex difference was found in alpine skiing (table 3).

WC, WSC and OWG competition injury incidence

The incidence of head/face injuries (n=96) in WC, WSC and OWG competitions (number of injuries per 1000 runs) was significantly higher in freestyle (1.8, 95% CI 1.2 to 2.4) than in alpine skiing (0.9, 95% CI 0.6 to 1.2; RR 2.05, 95% CI 1.25 to 3.46) and snowboard (1.0, 95% CI 0.6 to 1.3; RR 1.85, 95% CI 1.15 to 2.99). The competition head injury incidence across disciplines and subdisciplines is depicted in figure 1.

No sex differences were found in total for the three disciplines or within disciplines for head/face injuries occurring per 1000 competition runs (n=96; table 3).

DISCUSSION

This is the largest cohort study until now to examine the rate of head/face injuries in WC alpine and freestyle skiers and snowboarders. The majority of injuries were concussions and one in four injuries was severe. Freestyle skiers had the highest overall injury rate.

Table 3 Sex differences in the incidence of head/face injuries for snowboarders, freestyle and alpine skiers during seven seasons (2006–2013) of the FIS WC

	Males	Females	Risk ratio (95% CI)
All head/face injuries (n=245)			
Incidence (injuries per 100 athletes) with 95% CI			
Total all disciplines	3.9 (3.2 to 4.6)	5.8 (4.8 to 6.9)	1.48 (1.15 to 1.90)*
Snowboard	3.8 (2.7 to 4.9)	7.3 (5.2 to 9.4)	1.93 (1.27 to 2.91)*
Freestyle	4.5 (3.2 to 5.9)	7.4 (5.2 to 9.6)	1.63 (1.07 to 2.47)*
Alpine	3.4 (2.3 to 4.6)	3.6 (2.3 to 4.9)	1.05 (0.65 to 1.70)
WC, WSC and OWG head/face injuries (n=96)			
Incidence (injuries per 1000 runs) with 95% CI			
Total all disciplines	1.0 (0.7 to 1.2)	1.4 (1.0 to 1.8)	1.47 (0.98 to 2.20)
Snowboard	0.9 (0.5 to 1.3)	1.2 (0.6 to 1.8)	1.39 (0.69 to 2.78)
Freestyle	1.5 (0.8 to 2.2)	2.4 (1.3 to 3.5)	1.59 (0.82 to 3.09)
Alpine	0.7 (0.3 to 1.1)	1.1 (0.6 to 1.6)	1.55 (0.74 to 3.26)

*Significant difference (p<0.05).
FIS, International Ski Federation; OWG, Olympic Winter Games; WC, World Cup; WSC, World Ski/Snowboard Championships.

Disciplines

The head/face injury incidence was highest in freestyle, followed by snowboard and alpine skiing, respectively. Since all freestyle disciplines include aerial elements, this finding was not surprising.

In freestyle aerials, athletes perform inverted aerials with a take-off speed of around 70 km/h. The jumps range in height from 2 to 4 m and in inclination angle from 50° to 70°. Competitors land on a steep 37±1° landing hill of chopped snow.[13] One injury mechanism thought to be typical of aerials is a slapback episode where the skier over-rotates in the air, resulting in a backwards rotation after the ski tails contact the snow.[14] As the upper back and head contact the snow, athletes experience both direct head impacts and rotational acceleration of the head. Maximum head acceleration ranging from 27 to 92 g has been reported during slapback episodes.[14]

Slopestyle, ski cross and snowboard cross all contain challenging aerial features. In slopestyle, athletes ski/ride through a course including rails, jumps and other terrain park features, scoring points for amplitude, originality and quality of tricks.[15] Cross disciplines are a motocross-inspired mixture of freestyle and alpine events, characterised by courses which include banks, compressions, jumps and giant slalom-type turns.[16] Recent video analyses have revealed that the main injury situations in both cross disciplines involved jumping.[17 18]

For recreational snowboarders in a terrain park, a higher incidence of head injuries and concussions occurred on aerial features versus non-aerial features.[5] Skiers and snowboarders were more likely to suffer injuries to the head and concussions in a terrain park rather than on a traditional ski slope.[6] These findings correspond to our results, which show that freestyle athletes, who compete in courses containing several aerial elements, were at the highest risk of head/face injuries.

Sex differences

It should be noted that we detected a significant sex difference in the overall head/face injury incidence (per 100 athletes per season), but not in the competition head/face injury incidence (per 1000 runs). In all likelihood, this is due to a power problem caused by the limited number of competition injuries.

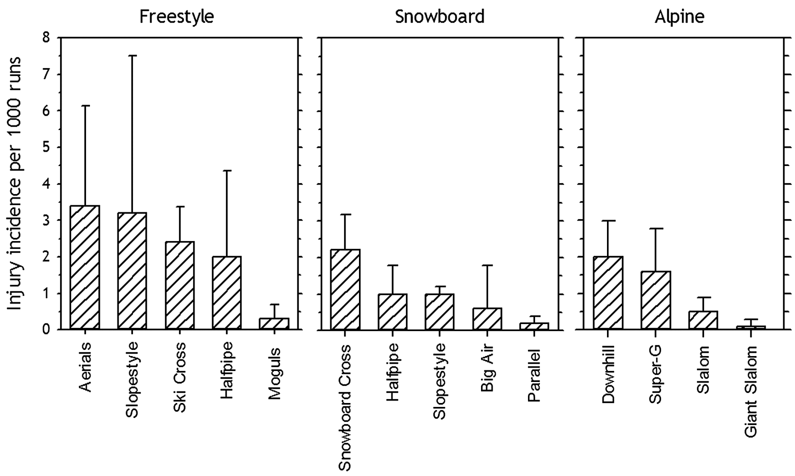

Figure 1 Head injury incidence (with 95% CI) per 1000 World Cup (WC), World Ski/Snowboard Championships and Olympic Winter Games competition runs for the different freestyle, snowboarding and alpine disciplines during seven seasons (2006–2013) of the International Ski Federation WC. Moguls include moguls and dual moguls. The snowboard parallel discipline includes parallel slalom and giant slalom.

Nevertheless, as can be seen in table 3, the risk ratios for injuries overall and in competition were consistent across disciplines, with the exception of the overall head/face injury rate in alpine skiing. Thus, it appears that women have about 1.5 times the risk of attaining a head/face injury compared with men.

Our results correspond with other studies, where women had an increased risk of concussion compared with men.[8] In US high school sports, girls had a 70% to a twofold increase in concussion risk compared with boys.[10 19] In our data, only men participated in big air competitions. Therefore, apart from in big air competitions, freestyle and snowboard men and women share courses and compete under the same conditions. Sharing the same course does not mean that men and women perform the same tricks or attain the same speeds or jumping heights. Men perform more challenging tricks than women, and attain higher speeds in, for example, ski cross and snowboard cross.[20] However, as we only have epidemiological data, we can only speculate about why women attain more head injuries. It may be hypothesised that courses and course elements designed to challenge the best male athletes may be too challenging for some women. Systematic video analyses of actual injury situations are needed to describe in detail the events leading to head injuries among men and women.

Severe head injuries

Almost 1/4 of reported head/face injuries were severe, causing at least 4 weeks of time-loss during the competitive season. Our injury registration method does not allow us to report how many of the severe injuries were season or career ending. Also, the study only covers the 5-month to 6-month competitive season, not the preparation period when athletes practise performing new tricks. However, during the 7-year observation period, two fatalities due to head injuries have occurred in our cohort (one in a ski cross competition and one in ski half pipe training). In other words, fatal head injuries represent a real concern among WC athletes. This is well documented from the recreational level, where head injuries and neurological injuries are the most common cause of death and disability for skiers and snowboarders.[4 7 21–23]

Prevention

Helmets reduce the risk of head injuries in recreational skiers and snowboarders, and are not thought to increase the risk of cervical spine injury or risk compensation behaviour.[24–26] For all WC alpine, freestyle and snowboarding events, the use of helmets is compulsory during course inspection, official training and competitions.[27] The helmets must be specifically designed and manufactured for the respective discipline, bear a CE mark and conform to established standards.[28–32] A new helmet standard for downhill, super-G and giant slalom is enforced from the 2013/2014 season, where the helmet, in addition to the existing standards, must pass a specific test with a test speed of 6.8 m/s compared with 5.4 m/s previously.[28]

The new helmet standard in alpine skiing represents an attempt at reducing the rate of severe head injuries, but more research is needed if injury rates are to be decreased in all disciplines. For instance, if rule changes or changes in course design are to be considered to decrease injury incidence or severity, clear-cut injury mechanisms must be identified.[33] Video analyses of injury situations would help us understand the mechanisms of head injuries in WC skiing and snowboarding, as they have done for knee injuries.[34–37]

In addition to continuing research into head injuries and helmet standards in alpine skiing, we suggest that future prevention strategies should address severe injuries across all disciplines, promote adequate recognition and medical attention for all head injuries, and target freestyle and snowboarding athletes, with particular attention to female athletes.

Methodological considerations

All injury recording during the seven WC seasons was through interviews with athletes, medical personnel or coaches. Recall bias is a challenge with retrospective interviews. However, a methodological study found that in the WC setting, retrospective interviews were the best method compared with prospective injury registration by team medical personnel or FIS Technical Delegates.[11] Interview forms based on the race schedules were used to help the interviewee recall the date, location and circumstances of injury.[11] Still, even if a recall bias may exist, we cannot see any reason why this should be sex or discipline related.

A greater problem could be that concussions are not recognised by athletes, coaches or medical personnel, and therefore are under-reported. Athletes might not self-report an injury they do not recognise as being harmful or dangerous at the time of competition.[38] Although much focus has been given to concussion recognition through recent consensus conferences, we do not know what the uptake of new guidelines have been in the skiing and snowboarding medical community.[33 39] From other sports, it is known that concussions are considerably under-reported, with the most common reason in football being that the athlete did not think the injury was serious enough to warrant medical attention.[40 41]

CONCLUSION

This is the largest cohort study until now to examine the rate of head injuries in WC alpine and freestyle skiers and snowboarders. The majority of head/face injuries were nervous system injuries/concussions and one in four injuries was severe. Freestyle skiers had the highest overall head injury incidence. Across all disciplines, the injury incidence was higher in women than in men.

What this study adds?

- This is the largest cohort study until now to examine the rate of head injuries in World Cup (WC) alpine and freestyle skiers and snowboarders.
- The majority of head injuries were concussions and one in four injuries was severe.
- Freestyle skiers had the highest overall head injury rate.
- Across all disciplines, the injury incidence was higher in women than in men.

How might it impact on clinical practice in the near future?

- Continued research into head injuries and helmet standards in all ski and snowboarding disciplines is needed.
- Future prevention strategies should address severe injuries across all disciplines, promote adequate recognition and medical attention for all head injuries, and target freestyle and snowboarding athletes, with particular attention to female athletes.
- Video analyses of injury situations would help us understand the mechanisms of head injuries in WC skiing and snowboarding.

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Contributors SES, TB and RB contributed to the study conception, design and methodology. SES and TB co-ordinated the study and managed the data collection. SES wrote the first draft of the paper, and all authors contributed to the final manuscript. SES and RB are the guarantors.

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Competing interests None.

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Head injuries among FIS World Cup alpine and freestyle skiers and snowboarders: a 7-year cohort study

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Paper II

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Head injury mechanisms in FIS World Cup alpine and freestyle skiers and snowboarders

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ABSTRACT

Introduction Head injuries represent a concern in skiing and snowboarding, with traumatic brain injuries being the most common cause of death.

Aim To describe the mechanisms of head and face injuries among World Cup alpine and freestyle skiers and snowboarders.

Methods We performed a qualitative analysis of videos obtained of head and face injuries reported through the International Ski Federation Injury Surveillance System during 10 World Cup seasons (2006–2016). We analysed 57 head impact injury videos (alpine n=29, snowboard n=13, freestyle n=15), first independently and subsequently in a consensus meeting.

Results During the crash sequence, most athletes (84%) impacted the snow with the skis or board first, followed by the upper or lower extremities, buttocks/pelvis, back and, finally, the head. Alpine skiers had sideways (45%) and backwards pitching falls (35%), with impacts to the rear (38%) and side (35%) of the helmet. Freestyle skiers and snowboarders had backwards pitching falls (snowboard 77%, freestyle 53%), mainly with impacts to the rear of the helmet (snowboard 69%, freestyle 40%). There were three helmet ejections among alpine skiers (10% of cases), and 41% of alpine skiing injuries occurred due to inappropriate gate contact prior to falling. Athletes had one (47%) or two (28%) head impacts, and the first impact was the most severe (71%). Head impacts were mainly on snow (83%) on a downward slope (63%).

Conclusion This study has identified several characteristics of the mechanisms of head injuries, which may be addressed to reduce risk.

INTRODUCTION

Head injuries represent a concern in alpine skiing, freestyle skiing and snowboarding.[1–7] Traumatic brain injuries (TBIs) are the leading cause of death in recreational skiers and snowboarders, and are linked to acrobatic and high-speed activities.[2 8] During the Vancouver 2010 Olympic Winter Games (OWG), the head and cervical spine were the most common injury locations for both men and women.[9] At the International Ski Federation (FIS) World Cup (WC) level, head and face injuries account for 10% to 13% of injuries that require medical attention in snowboarding, freestyle and alpine skiing[4 6 10]; 82% were concussions, and 24% of these led to an absence from training or competition for >28 days.[10] Since helmets are mandatory during official training, course inspection and competitions in all FIS WC events, these injury data cover a period where all athletes have been helmeted.[11]

A description of the inciting event, including a detailed characterisation of the head impact itself, is critical to understand the interaction of causative factors for head injuries among skiers and snowboarders.[12] Previous studies have described the injury mechanisms at the recreational level based on surveys and hospital data,[13–15] reconstructed specific head impact situations with anthropomorphic test devices or with computer modelling[16–18] or used helmet-mounted accelerometers to measure head impact forces.[19]

A more detailed and reliable analysis of the head injury mechanisms can be obtained using systematic analyses of video from real injury situations, compared with relying on descriptions of the injury mechanisms from, for example, the athlete, coach, accident reports or interview data.[20–22] Previously, the head impact kinematics of crashes have been described for a few cases. Yamazaki *et al* reconstructed one real case of a severe TBI in WC downhill skiing using a model-based image matching technique to describe the head impact kinematics.[23] In addition, the head impacts of four injury cases in WC snowboarders and freestyle skiers[24] and seven WC alpine skiers[25] have recently been reconstructed to describe the head impact kinematics.

However, no systematic video analysis of the mechanisms for head injury in WC snowboarders, alpine and freestyle skiers has been performed. Therefore, the aim of this study was to analyse head and face injuries recorded by the FIS Injury Surveillance System (ISS) through 10 seasons (2006–2016) of WC alpine and freestyle skiing and snowboarding to describe their mechanisms.

METHODS

Injury cases

All head/face injuries reported through the FIS ISS from WC and OWG alpine, freestyle and snowboard competitions during the period 2006–2016 were identified for video analysis.[1 4 6 7 10 26] Of the 123 injury cases, we obtained 57 injuries on video with the possibility of analysing the gross head injury mechanism (figure 1). We collected video recordings systematically from the WC television producer (Infront Media, n=53) and the IOC Multimedia Library (n=4) at the end of each WC season (2006–2016).

An injury is defined through the FIS ISS as “all injuries that occurred during training or competition and required attention by medical personnel”.[27] The classification of ‘head and face injuries’ does not include the neck or cervical spine. Injury severity is defined according to the duration

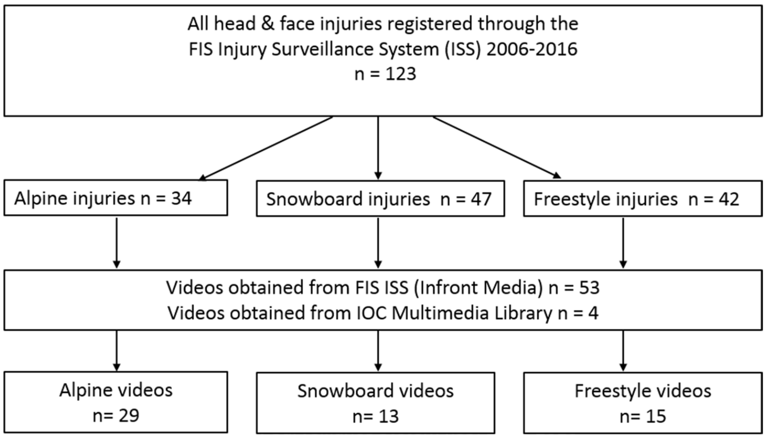

Figure 1 Flow chart of video acquisition process. FIS, International Ski Federation.

of absence from training and competition as slight (no absence), minimal (1–3 days), mild (4–7 days), moderate (8–28 days) and severe (>28 days).[28] The absence reported was attributed to the injury in question only. The definition of injury as well as the classification of injury type, body part injured and injury severity is based on a generalised definition and classification system used in injury surveillance, and not for head injuries, in particular.[27]

Video processing

All videos were converted to mp4 file format with H.264 encoding using Adobe Premiere Pro V.CS6 (Adobe Systems, San Jose, California, USA) and viewed using the frame-by-frame function in QuickTime V.7.7.9 (Apple, Cupertino, California, USA). The videos had frame rates of 25 Hz, 50 Hz and 60 Hz and the display aspect ratios were 4:3 or 16:9.

Video analysis form

We developed a specific analysis form for head/face injuries based on previous analysis forms used for analysis of injuries in alpine skiing and snowboard cross.[29–31] The analysis form included closed questions regarding (1) the skiing/riding situation and gross body biomechanics preinjury, (2) analysis of the head impact in detail and (3) postinjury security net contact. In addition, there was one open question where analysts were asked to describe the head injury mechanism in their own words (video analysis form—online supplementary appendix 1).

Video analysis

Five expert analysts in the fields of sports medicine (RB, AB, TB, SES) or head injury biomechanics (DAP) formed the analysis team. Initially, injury videos for each case were analysed independently using the form. During this phase, all analysts were blinded to the opinions of others, but were provided with injury information on each case (sex, discipline and specific diagnosis). The primary investigator then summarised the analysis forms from all five analysts. Consensus was said to have been reached if at least three analysts selected the same response. Cases for which consensus was not reached were discussed during a meeting attended by all experts. During the meeting, injury videos were reviewed as many times as required to obtain agreement.

Definition of main head impact injury frame

The five analysts used the frame-by-frame function of the video player to independently evaluate how many head impacts were visible in each case and to decide which head impact they classified as the main head impact. Consensus was reached during the group meeting regarding the main head impact in each case, which was used for the impact frame analyses.

All 57 videos were analysed with respect to the inciting event (injury mechanism), as it was possible to see the preimpact skiing/riding situation. However, in eight cases, we did not have a clear view of the number of head impacts, and in nine cases the impact location on the helmet was not visible.

Statistics

We performed a Mann-Whitney U test to assess whether there was any difference in injury severity between the head/face injury cases analysed and the cases where we could not obtain videos. To investigate the association between the number of head impacts and injury severity, a χ^2 test was performed, assuming linear by linear association. To achieve sufficient statistical power, we regrouped the number of head impacts into the following categories: one impact, two impacts, three or more impacts, excluding cases where the number of impacts could not be assessed. For both statistical tests, a two-sided alpha level of ≤ 0.05 was considered statistically significant. We used IBM SPSS Statistics V.24 (Armonk, New York, USA) for the analyses.

RESULTS

Injury cases

In alpine skiing, most of the cases were from the speed disciplines downhill (n=14) and super-G (n=11), followed by the technical disciplines giant slalom (n=2) and slalom (n=2). In snowboarding, the injuries occurred in snowboard cross (n=12) and slopestyle (n=1), whereas in freestyle skiing, the injuries occurred in ski cross (n=10), aerials (n=3), halfpipe (n=1) and slopestyle (n=1). There were 32 male (56%) and 25 female (44%) injured athletes. The age (mean±SD) of the athletes at the time of injury for alpine skiers, freestyle skiers and snowboarders was 27.0±5.7, 22.1±3.0 and 23.7±2.9, respectively. The most common diagnoses, across all disciplines, were concussions (n=39, 68%), followed by head/face fractures (n=6, 11%) and

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Table 1 Consensus decision on the number of visible head impacts and classification of the main head impact

No of head impacts				Classification of main head impact		
Head impacts	Alpine (n)	Snowboard (n)	Freestyle (n)	Alpine (n)	Snowboard (n)	Freestyle (n)
1	11	7	9	22	8	11
2	10	3	3	5	2	1
3	3	0	0	0	0	0
4	2	0	0	0	0	0
5	1	0	0	0	0	0
Not visible	2	3	3	2	3	3
Total (n)	29	13	15	29	13	15

contusions (n=6, 11%). The injuries were classified as severe in 14 cases (25%), moderate in 15 (26%) and mild in 12 cases (21%) (disciplines and medical information— online supplementary appendix 2). There was no significant (P=0.065) difference in injury severity between the head/face injury cases analysed (n=57) and the injury cases where we could not obtain videos (n=66).

Analysis of the main head impact

Most injury cases had one (n=27, 47%) or two (n=16, 28%) visible head impacts, and the first head impact was considered to be the main head impact in the majority of cases (n=41, 71%) (table 1). Among alpine skiers, 21% (n=6) of athletes experienced more than two head impacts. We could not assess the number of head impacts in eight cases (14%). There was no association between the number of head impacts and injury severity (P=0.260).

Table 2 Impact location on the helmet (n=57)

	Impact location				
Discipline	Face/front	Top	Side	Back	Not visible
Alpine	3	2	10	11	3
Snowboard	2	0	0	9	2
Freestyle	4	0	1	6	4
Total (n)	9	2	11	26	9

The most common impact location was the back of the helmet (46%), followed by the side (19%), the face or frontal part of the helmet (16%) and the top (4%) (table 2).

Most helmet impacts were on snow (n=47, 83%) and on a downward slope (n=36, 63%) (figure 2). In more than half of the cases, the helmet slid along the surface postimpact (n=29, 51%). In three alpine skiing cases, the helmet ejected during the head impact. No helmet ejections in the snowboard or freestyle cases were observed.

Postimpact, 17 athletes (15 in alpine skiing and two in freestyle skiing) were in contact with the security net, which functioned adequately in 16 (94%) of the cases. In one alpine skiing case, the security net did not function satisfactorily.

GROSS HEAD INJURY MECHANISMS

Alpine

Prior to the head impact situation, the majority of alpine skiers were turning (n=16, 55%) or landing after a jump (n=9, 31%).

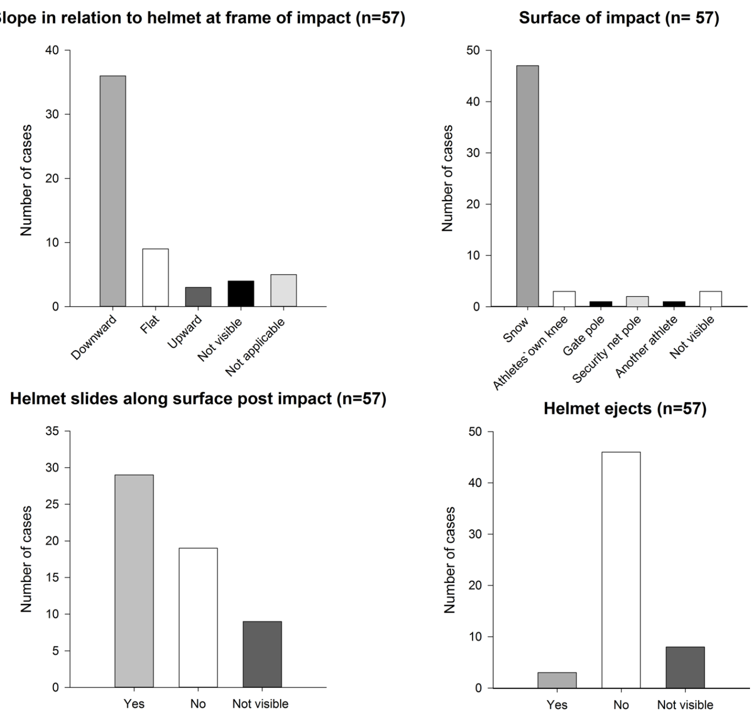

Figure 2 Analysis of the head impact frame (all disciplines, n=57).

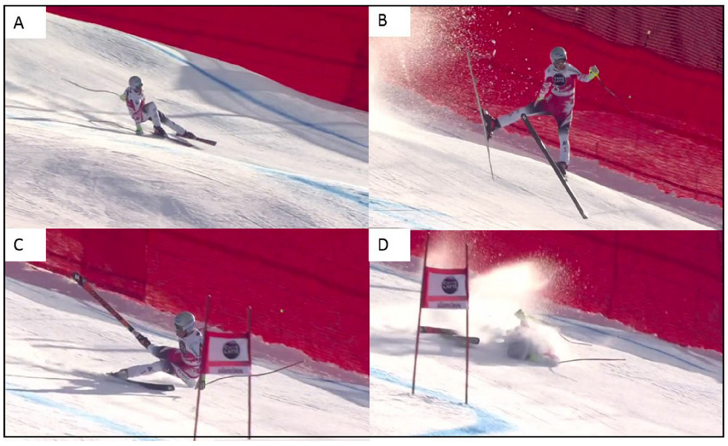

Figure 3 Alpine skier, typical example of a sideways fall. Key crash events: (A) The athlete is out of balance inwards and backwards after a jump. He loses pressure on the outer ski, which then catches the snow. (B–C) He hits a new bump, becomes airborne and yaws to the right, rolls to the left and pitches backwards. (D) The athlete lands on his left side and impacts the left side of the helmet (impact frame).

In all cases (n=29), the athlete made a personal technical or tactical mistake, leading to an out-of-balance situation. In 12 cases (41%), the athlete had inappropriate gate contact prior to crashing, causing the injury situation.

While still skiing prior to falling/crashing, they were out of balance in the frontal plane (roll), n=23, 79%, out of balance backward (rearward pitch), n=13, 45%, or forward (forward pitch), n=5, 17%, and/or out of balance in the transverse plane (yaw), n=12, 41%. In all alpine skiing cases, the crash sequence was characterised by the skis having initial contact with the landing surface, that is, the snow, followed by the lower and upper extremities, the buttocks/pelvis, back and trunk/chest, with the head being the last to impact the snow surface (see example in figure 3).

The gross body movement during the fall/crash, prior to head impact, was characterised by combinations of the athletes rolling (n=22, 76%), yawing (n=17, 59%) and/or pitching (n=15, 52%). The body rotation during the fall/crash was classified as moderate (90–180° in any direction) in 12 cases (41%), minor (<90°) in 11 cases (38%) or substantial (>180°) in 6 cases before head impact. The most common mechanisms of falling were sideways (n=13, 45%) or backward falls (n=10, 35%), followed by forward falls (n=4, 14%) or collisions (n=2, 7%) (figure 3).

Snowboard

Prior to the head impact situation, the snowboarders were landing after a jump (n=5, 39%), bank turning (n=2, 15%), in between elements (n=2, 15%) or had already crashed/fallen (n=3, 23%). A personal technical or tactical mistake contributed to the injury situation in eight (62%) cases. One athlete had inappropriate gate contact, which was the cause of injury. In five (39%) snowboard cross cases, the athlete made a forced error caused by contact with an opponent.

In 10 snowboarding cases where it was possible to analyse the crash sequence in detail, the crash sequence was characterised by the snowboard being in first contact with the snow, followed by the upper extremities, buttocks/pelvis, back, trunk/chest and lastly the head (figure 4).

All snowboarders were out of balance in the transverse plane (yawing) prior to falling/crashing (n=13, 100%), and most of the riders were also out of balance backwards (rearward pitch, n=12, 92%). Over half (n=8, 62%) of the snowboarders caught the back edge of the snowboard prior to head impact (see example in figure 4). The gross body movement during the fall/crash, prior to head impact, was characterised by combinations of the athletes pitching (n=13, 100%), yawing (n=8, 62%) and/or rolling (n=3, 23%), with minor (n=6, 46%), moderate (n=4, 31%) or substantial (n=3, 23%) body rotation. Snowboarders primarily fell backwards (n=10, 77%); however, two fell forwards (15%) and one collided with another athlete (8%).

Freestyle

Prior to the head impact situation, the majority of freestyle skiers were landing after a jump (n=10, 67%). The athletes fell or crashed in almost all cases (n=13, 87%). In two aerials cases, the freestyle athletes did not fall or crash; however, the athlete's face impacted their own knee during a forward pitch during landing. The majority of freestyle athletes (n=13, 87%) made a personal technical or tactical mistake prior to crashing. In two ski cross cases (13%), the athletes made a forced error caused by opponent contact.

It was possible to analyse the crash sequence in detail in nine freestyle cases. During the crash sequence, the skis were in first contact with the landing surface, followed by the upper extremities, buttocks/pelvis, back and trunk/chest, and the head was the last body part to impact the snow (see examples in figures 5 and 6).

Freestyle skiers were out of balance backwards (rearward pitch, n=8, 53%), rolling (n=5, 33%) and/or yawing (n=4, 27%) prior to crashing. The gross body movement during the fall/crash, prior to head impact, was characterised by the athletes pitching (n=9, 60%), yawing (n=6, 40%) and/or rolling (n=5, 33%), with minor (n=6, 40%), moderate (n=4, 27%) or substantial (n=2, 13%) body rotation. In three cases, the athletes had no visible body rotation precrash. Freestyle skiers primarily fell backwards (n=8, 53%), sideways (n=3, 20%), forwards (n=1, 7%) or did not fall/crash (n=2, 13%) (figures 5 and 6). In one freestyle case, the crash situation was not visible.

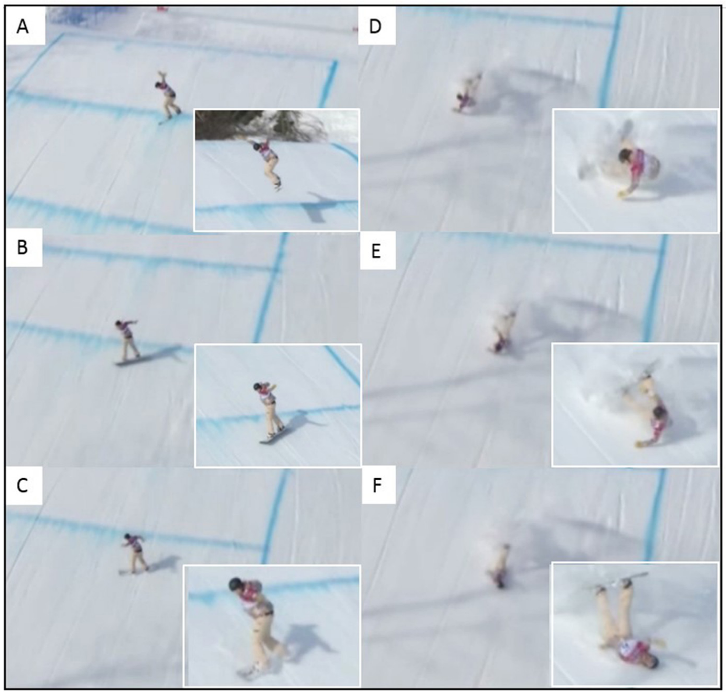

Figure 4 Snowboard cross, typical example of a back-edge catch. Key crash events: (A) The athlete is out of balance backwards and yawing during landing after a jump. (B) She continues to yaw on landing. Her bodyweight is first on the frontside edge of her snowboard. (C) Her bodyweight shifts to the backside edge. The back edge catches the snow surface. (D) She pitches backwards and impacts her buttocks, (E) followed by her upper extremity and back, (F) and then impacts the back of her helmet (impact frame).

DISCUSSION

The present study is the first to systematically analyse the mechanisms for head injuries in detail, including a substantial number of cases from elite alpine and freestyle skiing and snowboarding. Across all disciplines, most falls were backwards pitching and sideways falls, and we observed a common landing sequence during the crash situation: the athletes impacted the snow surface with their skis or board first, followed by the upper or lower extremities, buttocks/pelvis, back and, finally, the head. As a result of this crash sequence, impacts to the rear and side of the helmet dominated. It should also be noted that among alpine skiers, a high proportion of injuries resulted from inappropriate gate contact, and we observed three helmet ejections, which represents a concern.

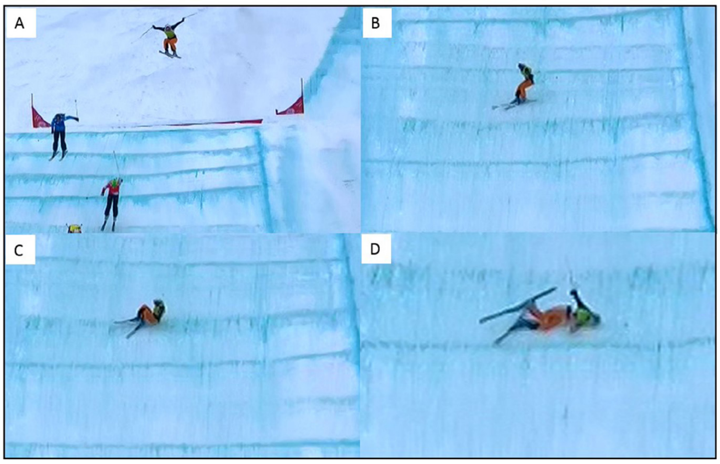

Figure 5 Freestyle ski cross, typical example of a backwards pitching fall. Key crash events: (A) Inappropriate course line and damping of jump. The athlete is out of balance backwards and yawing during the flight phase. (B) The athlete lands on skis with skis partially across the slope. (C) The athlete pitches backwards, impacting her buttocks. (D) Rolls to the side and impacts the side of the helmet (impact frame).

Figure 6 Freestyle aerials, example of a 'slapback' head impact. Key crash events: (A) The athlete is airborne during an inverted jump. (B) The athlete has over-rotated the jump and lands back-weighted. (C) Continues to rotate and pitches backward. (D) The back of the helmet impacts the snow (impact frame). (E) The head and upper body rebound up from the snow. (F) The athlete stands up fully.

Common crash sequence across disciplines

The athletes impacted the snow surface with their skis or board first, followed by the upper or lower extremities, buttocks/pelvis, back and, finally, the head (n=48, 84%). This information is important to increase the ecological validity of future head impact injury reconstructions. For example, a previous laboratory reconstruction of snowboarding back edge catches with anthropomorphic test devices presented them as being flipped up in the air after the edge catch, with the hips and spine in full extension and landing directly onto the head.[17] This is not a realistic reconstruction of a snowboarding back-edge catch event, based on our findings (see figure 4). The identification of this crash sequence may also be important for further development of wearable ski-racing airbags, specifically in relation to airbag deployment, that is, the triggering algorithm. Airbags were first used in official FIS WC races in the 2015/2016 season. However, further design improvements may be possible, particularly with respect to protecting the cervical spine and head in backward pitching falls, as described in the current paper.

Sideways falls common in alpine skiing

Among alpine skiers, sideways falls were common (45%). Two common patterns were observed. The athletes were either mainly out of balance in the frontal plane (roll) in air during flight, falling to the left or right hand side, impacting the side of the helmet, or the athletes landed mainly out of balance in the transverse plane (yaw) after flight, subsequently catching the ski edge and tripping. Being tripped, the athlete then fell sideways, also impacting the side of the helmet (figure 3).

Our findings are slightly contradictory to a recent study investigating head injury mechanisms in recreational skiers and snowboarders, where hospital data were combined with a survey based on sketches depicting the crash and impact locations.[13] Bailly *et* *al* reported that 'Falling head first' while skiing was the most common injury mechanism (28%), followed by 'Falling sideways (catching the ski edge)' representing 19% of skiers' falls.[13] The two main head impact locations were the frontal (57%) and facial (41%) areas.[13] However, for the sideways falls, they reported that 28% of head impacts were to the occipital region, which is similar to our findings.[13] This indicates that mechanisms of falling may be somewhat different between recreational and WC skiers, with recreational skiers having more impacts to the front/face and falling head first, although catching the ski edge and falling sideways has been identified as a common injury mechanism at both levels.

Backwards pitching falls common in freestyle and snowboard

Backwards pitching falls were the most common among snowboarders and freestyle skiers in our study. We observed two previously described types of backward pitching falls among our freestyle and snowboarding cases: 'slapback' injuries and back-edge catches.[19 32] The gross injury mechanism in 62% of our snowboarding cases was a 'back-edge catch' (opposite edge catch), which is previously described as a common head injury mechanism in snowboarders.[32 33]

Backward pitching falls were frequently observed in alpine skiing as well (35%). Bailly *et al* reported that falling backwards represented 14% of falls in recreational skiers, with the impact location being the occipital region in 73% of the backwards falls.[13] Backwards pitching falls may therefore be more common among WC alpine skiers compared with in recreational skiers.

Helmet ejections in alpine skiing: cause for concern

Among the alpine skiing cases, there were three helmet ejections at head impact (10% of cases). From the visual analysis, the cause of the helmet ejections cannot be determined. It could be that the helmet did not fit adequately, was not securely fastened or that the loads of the crash exceeded the stability of the helmet/strap.

One of the main requirements of a helmet is to provide and maintain appropriate and adequate coverage to the head, and a helmet that is poorly fitted or fastened may become displaced during normal use or even ejected during a crash.[34] Among cyclists, a recent study investigated the fit of helmets and reported that bicycle helmets worn by recreational and commuter cyclists are often the wrong size and often worn and adjusted incorrectly.[35] In addition, among motorcyclists, helmet type and wearing correctness were among the factors that affected the loads at which helmets became displaced.[34] However, the athletes in the current study were supported by professional teams and therefore likely received optimal advice and optimally fitted helmets from their equipment suppliers. Therefore, the helmet ejections observed represent a concern.

Many cases of inappropriate gate contact

In the alpine skiing cases, over 40% of the athletes had inappropriate gate contact, which threw the skier out of balance and ultimately led to the crash. In most cases, the gate contact resulted from a personal mistake of the skier (misjudging the turn/skiing line or having an inappropriate course line) and therefore hooking the gate with the upper extremity, impacting the gate panel, or straddling the gate with the inner ski. This is supported by previous video analysis of WC alpine skiing injuries in general, where in 30% of cases inappropriate gate contact caused the injury situation.[29] From the 2010/2011 season, FIS enforced the use of release gate panels, which must release from the pole when the athlete collides with the gate,[11] yet further design improvements may be possible.

Head impacts and impact location

Although most athletes experienced one head impact, many athletes (28%) experienced two, and in alpine skiing, some (21%) even more than two impacts. Alpine ski helmets have been demonstrated to provide protection against low-severity repetitive impacts, such as impacting slalom gates.[36] However, ski helmet liner materials exhibit degradation in performance for substantial repetitive impacts,[37] which may be an important consideration for helmet manufacturers with respect to helmet design and construction, although we did not detect an association between the number of head impacts and injury severity. However, we do not know whether the helmets used had suffered previous impacts.

Few impacts were to the front of the helmet or the face (16%); however, the face is mostly unprotected. In fact, we observed two cases in freestyle aerials where the athletes did not crash, but impacted their face onto their own knees, one suffering an orbital blow-out fracture. In contrast, at the recreational level, facial bone fractures and dental injuries are reported among male snowboarders and skiers to occur most frequently after falls or collisions with other persons.[38 39]

Head impact location, mainly to the back and side of the helmet, and impacting snow/ice (83%), may be important information for helmet manufacturers, as at the recreational level collisions with stationary objects or other skiers/riders might be more common.[40–43]

Helmets continue moving postimpact

In half of the cases, the helmet slid along the surface postimpact. A variable to evaluate helmet rebound motion up from the snow surface postimpact was not included in the video analysis form. In previous reconstructions of skiing and snowboarding head impact injuries, both linear and angular velocity changes indicated that there was a rebound phase immediately postimpact, which might not be anticipated in an impact with a compliant surface such as snow.[24] Although helmet rebound was not specifically investigated in this study, the helmet was observed to not stop moving postimpact in most cases.

Methodological considerations and limitations

The current study sample was derived from a systematic, prospective collection of injury videos over a 10-year period (2006–2016) based on the FIS ISS. We managed to acquire videos of 85% (29/34) of all WC alpine head and face injuries, ensuring that our sample of alpine injury videos is representative. However, we could only obtain videos of 28% (13/47) and 36% (15/42) of snowboarding and freestyle skiing head and face injuries, respectively, for the same period. This was mainly due to injuries not being videotaped by the television producer or the injury situation was not visible on the video. In addition, many head and face injuries in snowboard and freestyle skiing occur during qualification runs, which are not broadcasted. Therefore, the data from freestyle skiing and snowboarding should be interpreted with caution. Nevertheless, our findings parallel previous epidemiological literature.

We did not detect any difference in injury severity between the cases with and without video available; this suggests that the sample we were able to analyse is representative.

The injury recording was through interviews with athletes, medical personnel or coaches. Recall bias is a challenge with retrospective interviews. However, a methodological study found that in the WC setting, retrospective interviews was the best method compared with prospective injury registration by team medical personnel or FIS Technical Delegates.[28] Interview forms based on the race schedules were used to help the interviewee recall the date, location and circumstances of injury.[28] However, a limitation is that we did not have access to more detailed medical information, for example, the results of imaging studies done or standard severity scores such as Glasgow Coma Scale or Abbreviated Injury Scale.

A greater problem could be that concussions are not recognised by athletes, coaches or medical personnel, and therefore are under-reported. Athletes might not self-report an injury they do not recognise as being harmful or dangerous at the time of competition.[44 45] From other sports, it is known that concussions are under-reported to a large extent.[46–49]

Video quality and available camera views represent a challenge when determining the head impact frame and when assessing the gross injury mechanisms. It should be noted, however, that the assessment was consistent across analysts.

We included videos where the head impact frame was not visible. However, we could still perform an accurate analysis of the gross body biomechanics leading up to the head injury, which provides novel and valuable information.

Further perspectives

Based on the three helmet ejections we observed, it seems prudent to ensure that FIS WC athletes have optimally fitting helmets, which are fastened correctly, as this could potentially be an area of improvement with respect to athlete safety.

Our observation that the helmet continues moving post-impact, combined with findings from previous papers[24 25] describing a linear and angular rebound motion up from the snow surface, could be an important consideration for helmet manufacturers. Both the helmet and the snow impact surface may contribute to rebound, and future helmet standards could potentially address these issues.[24 25]

Based on information about real gross head injury mechanisms, future biomechanical studies could reconstruct realistic crash sequences, as this might help our understanding of the comparability of laboratory reconstructions or computer modelling and real head impact injuries on a snow surface.

FIS has developed gates with panels/poles offering less resistance or with an optimised release mechanism when hooking. This effort should continue based on the high number of inappropriate gate contacts that lead to head injuries (and knee injuries)[29] in alpine skiing.

In snowboarding and freestyle skiing, most head injuries occurred during landing from a jump or when crashing while passing an element. The primary focus for course design should therefore be on safe jump and landing constructions, and on the design of elements, such as banked turns. Several previous studies using computer modelling techniques have investigated if the creation of safer terrain park jump designs that reduce the risk of impact injuries is possible.[50–53] In particular, it has been discussed if the severity of impact risk can be characterised by equivalent fall height, a measure of jumper impact velocity normal to the slope.[51] The thought is that the smaller the equivalent fall height, the smaller the probability of serious injury resulting from impacts normal to the snow surface.[52] However, the crash sequence we described, with the skis/board having initial contact, followed by the extremities, buttocks, back and lastly the head, could mean that not only the normal-to-slope equivalent fall height could be of importance to the impact severity, but this pitching motion could possibly also contribute to the severity of head impact injury. We therefore reiterate the necessity of future biomechanical studies to reconstruct crash sequences realistically.

In alpine skiing, safe course design in general, and not only for jumps, must be a priority. Further investigations into the reasons athletes make mistakes during turning, and into the causes of inappropriate gate contact, are therefore warranted, in addition to addressing jump safety. Spörri *et al* reported that the main perceived risk factors among alpine expert stakeholders were system ski, binding, plate and boot; changing snow conditions; physical aspects of the athletes; speed and course setting aspects and speed in general.[54] Gilgien *et al* reported that in fall or crash situations, the magnitude of speed is of particular importance since speed determines the kinetic energy that has to be dissipated during a crash impact.[55] In technically demanding sections such as jumps, rough terrain and turns, anticipation and adaptation time decrease with speed and mistakes might be more likely to occur.[55] Simulation models of jump landings in WC downhill skiers suggested that limited preparation time, high take-off speeds, steep take-off angles and landings in flat terrain had the most influence on landing impact injury risk.[56] It therefore seems reasonable to suggest that reducing skier speeds especially during turns and terrain transitions, and focusing on optimal safety jump design would reduce injury risk.

What are the findings?

- This is the first study to use video analysis to systematically analyse a substantial number of head and face impact injury cases among International Ski Federation World Cup alpine and freestyle skiers and snowboarders.
- We identified a common landing sequence during the crash, where the athletes impacted the snow surface with the skis or board first, followed by the upper or lower extremities, buttocks/pelvis, back and, finally, the head.
- Gross head injury mechanisms were characterised mainly by backward pitching falls with impacts to the rear of the helmet in all disciplines, and also by sideways falls and impacts to the side of the helmet in alpine skiers.
- Many athletes experienced two or more head impacts, which may be an important consideration for helmet manufacturers with respect to helmet design and construction.

How might it impact on clinical practice in the future?

- Potential at-risk situations for head and face injuries have been identified, which might help inform athletes, coaches and event organisers.
- Knowledge about gross head and face injury mechanisms can provide valuable information for event organisers and course builders with respect to designing safer courses and jumps in the future.
- This study gives valuable information about gross head injury mechanisms for helmet manufacturers, for developers of other safety equipment such as wearable airbags, for designers of ski gate poles and panels, and for future studies aiming to reconstruct realistic head impact injury mechanisms among skiers and snowboarders.

CONCLUSION

Head and face injuries among FIS WC alpine and freestyle skiers and snowboarders mostly occurred while turning or landing from a jump. Most falls were backwards pitching and sideways falls, with a common crash sequence of impacting the snow surface with the skis or board first, followed by the upper or lower extremities, buttocks/pelvis, back and finally the head. Impacts to the rear and side of the helmet dominated, and most athletes experienced one or two head impacts. In alpine skiing, the high number of injuries occurring due to inappropriate gate contact, and the proportion of helmet ejections observed represent a concern.

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Head injury mechanisms in FIS World Cup alpine and freestyle skiers and snowboarders

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Paper III

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Head impact velocities in FIS World Cup snowboarders and freestyle skiers: Do real-life impacts exceed helmet testing standards?

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ABSTRACT

Introduction Prior to the 2013–2014 season, the International Ski Federation (FIS) increased the helmet testing speed from a minimum requirement of 5.4 to 6.8 m/s for alpine downhill, super-G and giant slalom and for freestyle ski cross, but not for the other freestyle disciplines or snowboarding. Whether this increased testing speed reflects impact velocities in real head injury situations on snow is unclear. We therefore investigated the injury mechanisms and gross head impact biomechanics in four real head injury situations among World Cup (WC) snowboard and freestyle athletes and compared these with helmet homologation laboratory test requirements. The helmets in the four cases complied with at least European Standards (EN) 1077 (Class B) or American Society for Testing and Materials (ASTM) F2040.

Methods We analysed four head injury videos from the FIS Injury Surveillance System throughout eight WC seasons (2006–2014) in detail. We used motion analysis software to digitize the helmet's trajectory and estimated the head's kinematics in two dimensions, including directly preimpact and postimpact.

Results All four impacts were to the occiput. In the four cases, the normal-to-slope preimpact velocity ranged from 7.0(±SD 0.2) m/s to 10.5±0.5 m/s and the normal-to-slope velocity change ranged from 8.4±0.6 m/s to 11.7±0.7 m/s. The sagittal plane helmet angular velocity estimates indicated a large change in angular velocity (25.0±2.9 rad/s to 49.1±0.3 rad/s).

Conclusion The estimated normal-to-slope preimpact velocity was higher than the current strictest helmet testing rule of 6.8 m/s in all four cases.

INTRODUCTION

According to the SnowSport Industries America, in the 2014–2015 season, there were approximately 7.7 million snowboarders (62% male, 38% female) and 4.5 million (59% male, 41% female) freeskiers in the USA alone.[1] However, recent studies have documented that injury rates in snowboarding and freestyle skiing are high, both at the competitive and recreational level.[2–6]

At the International Ski Federation (FIS) World Cup (WC) level, head injuries account for 12% of injuries that require medical attention in freestyle, alpine and snowboarding athletes.[7] Of these, 82% are concussions of which 24% are severe, leading to an absence from training or competition for more than 28 days.[7] However, this severity rating is an operational injury definition typically used for injury surveillance in sports, and not a head injury-specific severity rating.

Traumatic brain injuries (TBIs) are the leading cause of death in recreational skiers and snowboarders and are linked to acrobatic and high-speed activities.[5 8] In terrain parks, the majority of injuries occur on jumps and aerial features that promote a large drop to the ground.[9 10] Snowboarders are significantly more likely to sustain head/neck or trunk injuries than upper extremity injuries on aerial features, and the most commonly injured anatomic location for skiers using aerial features in a terrain park is the head.[11 12]

Helmets can prevent skull fractures and catastrophic head injuries, although the ability to prevent concussion is less clear.[13] There is the potential for a helmet to change the burden of injury by converting a potentially serious brain injury incident into a concussion incident. Several previous epidemiological studies among recreational skiers and snowboarders, including two case –control studies and a long-term (1995/1996–2011/2012) prospective epidemiological study, have documented that the use of helmets significantly reduces the risk of head injury and does not increase the risk of neck injury.[14–18]

In all FIS WC events, helmets are mandatory during official training, course inspection and competitions.[19] Prior to the 2013–2014 WC season, FIS enforced a new helmet testing rule for alpine downhill, super-G and giant slalom and for freestyle ski cross.[19] Under the new safety rule, helmets must be certified to both American Society for Testing and Materials (ASTM) F2040 and European Standard(EN) 1077:2007 (class A) standards. In addition, the helmets are required to pass a 6.8 m/s impact energy attenuation drop test using the EN 1077 method. The additional test corresponds to a drop height of 2.4 m.[19] However, this new, stricter rule has not been enforced by FIS for snowboarding or for the other freestyle disciplines.[19]

Since the start of the FIS Injury Surveillance System in 2006/2007, it has been mandatory for snowboard and freestyle skiing helmets to comply with either EN 1077 (Class B) or ASTM F2040, as minimum standards.[19] However, helmets fulfilling higher safety standards such as EN 1077 (Class A) or Snell Memorial Foundation (Snell) RS-98 could also be used.[19] The EN 1077 test standard has a pass/fail criterion for peak linear maximum headform acceleration of 250 g (g_{max} <250 g) in flat anvil impacts at 5.4 m/s.[20] In comparison, the pass/fail criteria in both the ASTM F2040 and Snell RS-98 standards is 300 g peak linear headform acceleration (g_{max} <300 g) in 6.2 m/s and 6.3 m/s, respectively, flat anvil impacts.[21 22]

Previous research has documented the need to target future injury reduction strategies in snowsport helmet design towards both severe head injuries and concussions.[23] The new helmet rule represents an attempt to reduce the rate of severe head injuries. Helmets are predominantly designed for impacts on rigid surfaces (such as roads or pavements) and not for impacts on more compliant surfaces such as snow or ice.[24] Impact surfaces in helmet testing standards are mainly rigid steel anvils. These test surfaces are not designed to simulate real-world conditions but rather to represent severe impact surfaces that allow helmet performance to be evaluated and facilitate test repeatability and reproducibility.[24] Therefore, future helmets should be developed and evaluated also with regard to realistic impact conditions, such as impacts onto snow and ice for skiing and snowboarding helmets.[23]

Recent studies based on numerical modelling or anthropomorphic test devices have described snowboarding normal-to-slope head impact velocities of 7.8±1.7 m/s and 8.11 m/s.[25 26] These studies indicate that head impact velocities might be slightly higher than the new strictest helmet testing rule.[25 26] However, how these studies, and the increased helmet testing speed, relate to head impact velocities in real head injury situations on snow is unclear.

The current direction in helmet development and testing is to consider the capacity of helmets to manage the head's angular kinematics (acceleration and/or velocity).[23 27 28] At present, angular kinematic management is not considered in any national or sports-specific standard. Therefore, it is of interest to describe angular kinematics during helmeted real-world impacts in as much detail as possible, with the data obtained from this video analysis.

Our study aims were: (1) to describe the injury mechanisms in a selection of head impact injury cases among WC snowboard and freestyle athletes, (2) to describe the gross head impact biomechanics and (3) to compare the head impact characteristics with relevant helmet standards.

METHODS

Medical information

Medical information about the selected cases was obtained through the FIS Injury Surveillance System (FIS ISS) based on data from 8 WC seasons (2006–2014).[2–4 29] A total of 75 WC competition head/face injuries (snowboard n=40, freestyle n=35) were registered in the FIS ISS database during eight seasons (figure 1). Medical information about one case was obtained through the IOC injury and illness surveillance system for multisport events, used during the 2014 Winter Olympic Games in Sochi, Russia (figure 1).[30]

Video collection and processing

All videos from the FIS WC competitions were collected retrospectively at the end of each of the eight seasons from the FIS WC television producer (Infront Media). As only competition runs are filmed by the television producer, no videos of warm-up or training runs were acquired. One additional video (case 4) was obtained from the IOC Olympic Multimedia Library. Of the 76 head injuries recorded, we obtained 16 videos with a clear view of the incident (figure 1). In other cases, the camera view of the incident was obscured by snow spray, athletes, the terrain

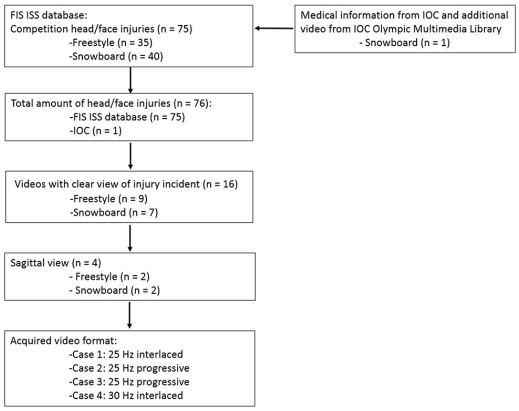

Figure 1 Flow chart of the video acquisition process. FIS ISS, International Ski Federation Injury Surveillance System; IOC, International Olympic Committee.

(bumps and jumps) and camera zooming or panning, athletes crashing out of camera view or other circumstances (figure 1).

The main criterion for including the videos was a primarily sagittal view of the athlete during the incident. Of the 16 (FIS n=15, IOC n=1) available videos of competition injuries, only four met this criterion. Two of the videos obtained had a progressive scan with a frame rate of 25 Hz, while two of the videos were obtained in an interlaced format, making it possible to double the effective frame rate to 50 Hz and 60 Hz (figure 1). We deinterlaced and edited the videos using Adobe Premiere Pro CS6 (Adobe Systems, San Jose, California, USA). We edited the videos to obtain square pixels (1:1 pixel aspect ratio), and the videos had a display resolution of 1024×576 pixels (case 1), 788×576 pixels (cases 2 and 3) and 1920×1080 pixels (case 4). We obtained the ski or snowboard dimensions from the athlete or their ski/snowboard supplier. The ski/snowboard lengths ranged between 150 cm and 191 cm. Based on this information, we could calculate the pixel size to range from 0.8 cm to 1.3 cm. The pixel size was calculated at the ski/snowboard measurement frame.

Linear movement analysis

A commercial software programme for video-based movement analysis (SkillSpector, V.1.3.2, Odense, Denmark) was used to digitise a fixed point on the helmet, as well as two reference points in the surroundings. The local calibration frame was positioned at the frame of helmet impact, using the length of the ski/snowboard for scaling. The measurement of the ski/snowboard was performed at the closest possible frame to the frame of impact where we could see the ski/snowboard perpendicularly and in full length. As we could not see the ski/snowboard perpendicularly and in full length during the helmet impact frame in any of the cases, the measurement frame is therefore not the same as the calibration frame. The mean time from the measurement frame to the calibration frame for all four cases was 0.3 s. The calibration frame was positioned in relation to the slope of the surface during the helmet impact. We could only assess the slope of the surface in the sagittal plane. We assumed that the vertical direction of the video footage was aligned with the true vertical axis.

We used a smoothing spline algorithm with a 15 Hz cut-off to calculate head velocity.[31] To determine the change in linear

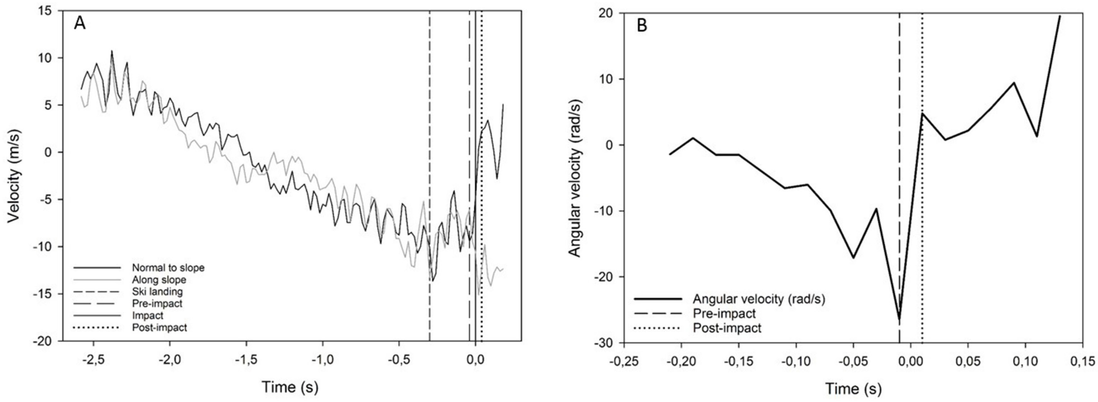

Figure 2. **(A)** Estimated filtered velocity of the digitised helmet point of case 1, including the ski landing frame (−0.30 s) and preimpact (−0.04 s) and postimpact (0.04 s) frames, used as variables to describe the velocity change in the normal-to-slope and along-slope directions. (B) Estimated helmet angular velocity in the sagittal plane (unfiltered) of case 1, including the preimpact (−0.01 s) and postimpact (0.01 s) frames. The impact frame (0.0 s) is midway between the preimpact and postimpact frames.

velocity in the normal-to-slope and along-slope directions, we extracted variables from preimpact and postimpact frames, immediately before and after (maximum two frames (40 ms)) the head impact (figure 2A). The lowest downwards velocity immediately preimpact was reported, in addition to the highest upwards velocity immediately postimpact (figure 2A).

Error assessment

The same person performed three digitising trials of the helmet for each case and we report the mean±SD of the three trials. As a measure of the intrarater digitising error, we calculated the root mean square error (cm) of the helmet position (normal and along slope) between the three digitising trials for all four cases and report the mean. Furthermore, we performed three digitising trials of the pelvis during the flight phases and fitted a linear regression line for the mean velocity of the pelvis for the flight phases of cases 1, 2 and 4 (case 3 did not have a flight phase). For the digitisation of the pelvis, it was possible to perform the ski/board measurement and the calibration in the same frame. The calibration frame was aligned with the video image.

We reported the root mean square error (m/s) from the regression line of the flight phases in both the vertical and horizontal directions (figure 3); the estimated vertical and horizontal acceleration of the estimated centre of mass (represented by the pelvis) due to gravity during the flight phases of cases 1, 2 and 4 (figure 3); and the root mean square error of the three trials of the angular measurement of the helmet.

Head impact angle

The head impact angle is defined as the angle of the head velocity vector prior to impact relative to the slope at the frame of impact. The head impact angle is therefore not the orientation of the helmet to the snow.

Angular movement analysis

We measured the sagittal plane angular velocity of the helmet frame by frame, from at least 10 frames preimpact to at least five frames postimpact, using an angle measurement software (MB Ruler V.5.3, Markus Bader—MB Software Solutions). We aligned the MB Ruler visually with an estimated alignment close to the Frankfurt plane, represented by the goggle band, on a frame-by-frame basis. We did three trials for each case and we report the mean angular velocity. Angular velocity was estimated as the change in angle between two frames divided by the time interval. No filtering was done. To estimate the change in angular velocity, we used the lowest negative point of the preimpact angular velocity and the peak of the postimpact angular velocity (maximally two frames (40 ms or less) before and after the impact) (figure 2B).

Injury severity

The FIS ISS classifies injury severity according to the duration of absence from training and competition as: slight (no absence), minimal (1–3 days), mild (4–7 days), moderate (8–28 days) and severe (>28 days).[29] This classification of injury severity is an operational injury definition within the FIS ISS (where all

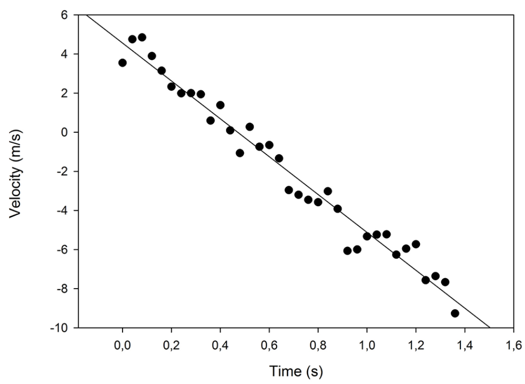

Figure 3 Vertical velocity of the flight phase of case 2, fitted with a linear regression line to estimate vertical acceleration due to gravity and the root mean square error (m/s).

Table 1 Description of the four head impact injury cases

	Case 1	Case 2	Case 3	Case 4
Sex	Male	Male	Female	Female
Age at time of injury	21	18	21	24
Season of injury	2012/2013	2007/2008	2010/2011	2013/2014
Diagnosis	Concussion	Concussion	Concussion	Concussion
Severity (absence)	4–7 days	4–7 days	8–28 days	0
Discipline	Ski halfpipe	Ski cross	Snowboard cross	Snowboard slopestyle
Competition	World Cup competition	World Cup competition	World Cup competition	Olympic Winter Games

injuries and not only head/face injuries are registered) and therefore not a head injury-specific definition of severity.

RESULTS

The four head impact injury cases analysed were from four different freestyle and snowboard disciplines and all resulted in concussion (table 1; figures 4–7). In all four cases, the impact location was to the rear of the helmet. In the two skiing situations, the athlete landed rear-weighted and fell backwards while the skis were pointing in the direction of movement. In contrast, the two snowboard injuries resulted from catching the back edge when the athlete had her back to the direction of movement.

Linear velocity

The normal-to-slope preimpact velocity ranged from 7.0±0.2 m/s to 10.5±0.5 m/s and the normal-to-slope velocity change ranged from 8.4±0.6 m/s to 11.7±0.7 m/s (table 2). For all cases, there was a greater change in velocity from preimpact to postimpact in the normal-to-slope direction compared with the along-slope direction (table 2, figure 2A). For cases 2, 3 and 4, the contribution of the along-slope component was minor. However, for case 1, the along-slope component was substantial (table 2).

The impact angles of the head velocity vector relative to the slope at the frame of impact were 57°, 25°, 54° and 45° for cases 1 to 4, respectively.

Angular velocity

All cases displayed peak head angular velocity immediately prior to impact. The peak ranged from 42.7±0.5 to 22.9±1.4 rad/s (figure 2B; table 2). Within 40 ms of impact, there was a rebound motion of the head in all cases. The maximum rebound angular velocity ranged from 2.1±1.6 to 8.1±0.5 rad/s. The total change in angular velocity ranged from 25.0±2.9 to 49.1±0.3 rad/s (table 2).

Estimation of error

The root mean square error of the vertical velocity of the pelvis during the flight phases was 1.55 m/s, 0.71 m/s and 0.47 m/s from the regression line for cases 1, 2 and 4, respectively. Standard acceleration due to gravity is 9.81 m/s², and is therefore the target value for our vertical acceleration estimates. The acceleration due to gravity during the flight phases was estimated to be 10.3 m/s², 9.7 m/s² and 10.7 m/s² for cases 1, 2 and 4. Our target measure for the horizontal component of the gravitational acceleration is 0 m/s². The horizontal acceleration was 0.7 m/s², 2.7 m/s² and 1.3 m/s², and the root mean square error in the horizontal direction was 1.7 m/s, 1.4 m/s and 0.8 m/s for cases 1, 2 and 4, respectively.

The mean root mean square error of the three digitising trials of the helmet of cases 1 to 4 in the normal-to-slope direction was 1.9 cm and 1.7 cm in the along-slope direction .

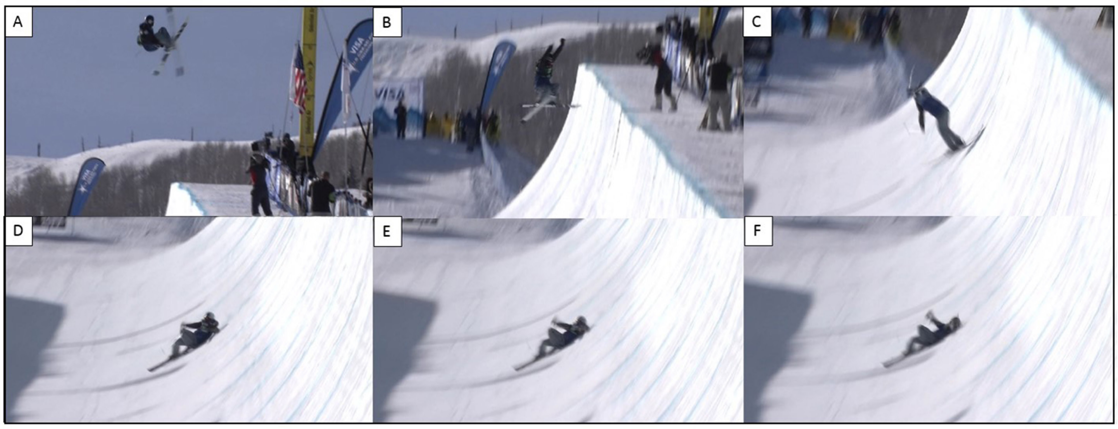

Figure 4 Case 1 (50 Hz). Key crash events: (A) the highest point of the athlete's trajectory, (B) descending towards the vertical part of halfpipe wall, (C) ski landing frame (first impact of ski tails), (D) buttocks and lower back contact with snow, (E) upper back contact with snow, (F) head impact frame.

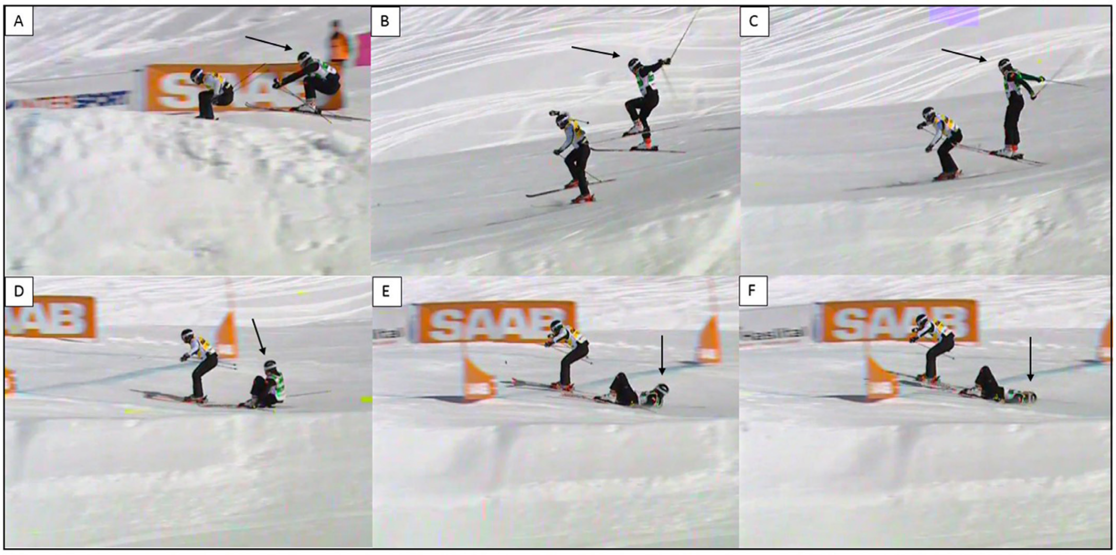

Figure 5 Case 2 (25 Hz). Key crash events (the black arrows point to the injured athlete): (A) the athlete is in flight following a jump, (B) the athlete loses balance during flight, creating an out of balance movement backwards, (C) ski landing frame (first contact of tails of skis), (D) buttock contact with snow. Trunk and hip in flexed positions, (E) upper back contact with snow. Hip and trunk extend. The athlete's shoulders extend, (F) head impact frame.

Figure 6 Case 3 (25 Hz). Key crash events: (A) the athlete is approaching a banked turn, (B) the athlete loses control of her board and her back edge catches, (C) the body rotates about the board, (D) the athlete continues to rotate and translate along the ground. The hip and trunk are maximally flexed, (E) the athlete lands on her buttocks and continues to rotate posteriorly while the hip and upper body extends. The athlete extends her shoulders, (F) head impact frame.

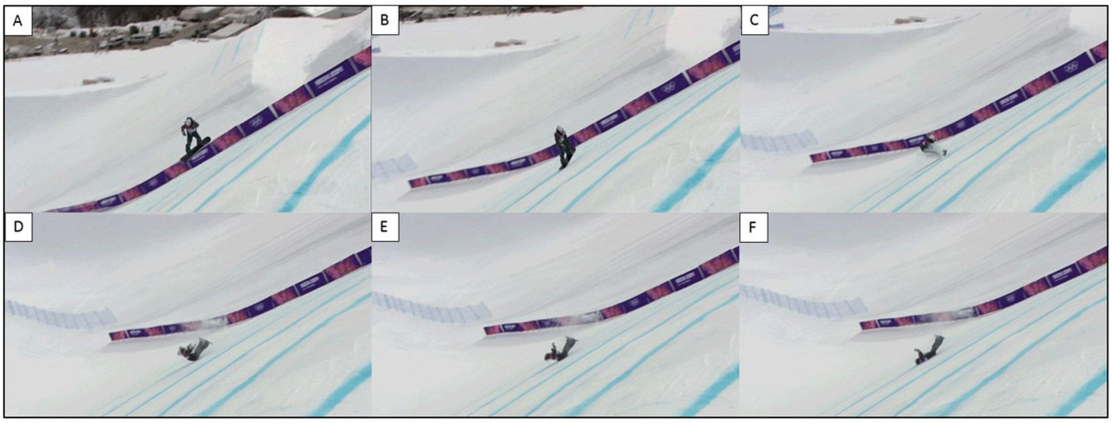

Figure 7 Case 4 (60 Hz). Key crash events: (A) the athlete is airborne, approaching her landing, (B) board landing frame (first contact of board to snow), (C) the back edge catches.The body rotates about the board. The hip and trunk are maximally flexed, (D) the athlete continues to rotate and translate along the ground and lands onto her buttocks, (E) extension of the hip and trunk, (F) head impact frame.

The mean root mean square error of the three trials of the angular measurement of the helmet was 3°.

DISCUSSION

This is the first study to report head impact velocities of real concussive events in FIS WC snowboarding and freestyle skiing. In all four cases, the estimated normal-to-slope preimpact velocity was greater than the prevailing minimum requirements at the time of the incidents of 5.4 m/s (EN 1077), 6.2 m/s (ASTM F2040) and the current FIS helmet rule of EN 1077 plus ASTM F2040 plus 6.8 m/s impact test for alpine giant slalom, super-G and downhill and freestyle ski cross. The change in head velocity during impact in the normal-to-slope direction ranged from 8.4±0.6 m/s to 11.7±0.7 m/s. For three of the four cases, the along-slope velocity change was minor, while in one case, the along-slope component was substantial. However, the significance of this along-slope velocity change in relation to helmet testing standards is unclear. The sagittal plane angular velocity estimates indicated a rapid backwards head rotation with a large change in angular velocity (25.0±2.9 rad/s to 49.1±0.3 rad/s) during impact.

Gross injury mechanisms

Our four injury cases represent common head impact scenarios in snowboarding and freestyle skiing. The gross injury mechanism of our two snowboarding cases (cases 3 and 4) was a ‘back-edge catch’ , which is previously described as a common head gross injury mechanism in snowboarders.[32] Previous studies have described that the most frequent causes of snowboarding head injuries are simple falls on slopes in beginners and falls during jumping in experts, while the most common injury mechanism is falling backwards, leading to an occipital impact.[33–35]

The gross injury mechanisms of our two freestyle skiing cases (cases 1 and 2) are similar to ‘slapback’ mechanisms in aerials skiers. In aerials skiers, slapback head injuries typically occur when a skier over-rotates in the air during an inverted

Table 2 Estimated linear velocity of the digitised helmet points including the change in head velocity, and estimated angular velocity of cases 1 to 4 (±SD for the three trials). Negative velocity refers to downward movement (towards the slope) in the normal-to-slope direction, while positive velocity refers to a rebound (upwards) movement. Negative angular velocity refers to a head rotation towards extension, while positive angular velocity refers to a head rotation towards flexion. A negative velocity change in the along-slope direction indicates a decrease in velocity from preimpact to postimpact, while a positive along-slope velocity change indicates an increase

	Case number	Frame rate analysed (Hz)	Preimpact velocity (±SD)	Postimpact velocity (±SD)	Change in velocity (±SD)
Normal-to-slope velocity (m/s)	1	50	−9.4 (0.3)	2.3 (0.7)	11.7 (0.7)
	2	25	−7.0 (0.2)	1.4 (0.5)	8.4 (0.6)
	3	25	−8.9 (0.1)	1.1 (0.2)	10.0 (0.3)
	4	60	−10.5 (0.5)	0.2 (0.1)	10.7 (0.6)
Along-slope velocity (m/s)	1	50	6.1 (0.1)	12.3 (0.6)	+6.2 (0.7)
	2	25	15.1 (0.1)	17.4 (0.1)	+2.3 (0.1)
	3	25	6.5 (0.2)	5.6 (0.1)	−0.9 (0.2)
	4	60	10.6 (0.5)	8.3 (0.6)	−2.3 (0.9)
Angular velocity (rad/s)	1	50	−26.4 (1.3)	4.8 (2.0)	31.2 (3.2)
	2	25	−22.9 (1.4)	2.1 (1.6)	25.0 (2.9)
	3	25	−42.7 (0.5)	6.4 (0.4)	49.1 (0.3)
	4	60	−32.2 (3.2)	8.1 (0.5)	40.3 (3.1)

jump, causing further backward rotation after the ski tails have contacted the snow, with the back and head ultimately impacting the landing surface.[36] Our freestyle cases were not aerials skiers, and there is an important differences in the landing dynamics of aerials skiers compared with our two cases: aerials skiers land on a steep landing zone (37°) with chopped snow, as opposed to our freestyle cases who landed on hard snow in flatter areas.[37] Both freestyle aerials and half pipe athletes (case 1) perform inverted jumps, while in ski cross (case 2) this is not the case. In addition, in freestyle aerials, due to the steepness of the landing slope, the skiers do not usually impact the snow with their buttocks. Nevertheless, despite these differences, the slapback head injury mechanism seems to be similar in our two cases compared with aerials skiers.

Considering the gross injury mechanisms, our cases of snowboarding back edge catches demonstrated different crash dynamics than previous studies using laboratory reconstructions with Hybrid III anthropomorphic test devices.[25 38] These studies demonstrated anthropomorphic test devices being flipped up in the air after the edge catch, with the spine and hips in full extension, before landing on the head, without the buttocks or back contacting the snow.[25 38] In contrast, the observed gross injury mechanism in our study involved the following sequence: edge catch, buttock contact with snow, back contact and finally head contact with snow (figures 6 and 7). Richards *et al*[25] reported that the mean normal-to-slope head impact velocity was 8.11 m/s, corresponding to a helmet drop height of 3.4 m, and the resultant velocity was 10.6 m/s, which despite the differences in study approach and crash mechanism is very similar to our results.

One previous study can help shed light on the forces involved in slapback mechanisms. Meacham *et al*[36] instrumented the helmets of aerials skiers with triaxial accelerometers and reported maximum impact accelerations during real-life slapbacks of 27–92 g with a maximum duration of impacts of 12–96 μs.[36] Severity indices were considered low in terms of life-threatening injury levels. However, as Meacham *et al*[36] did not report velocity changes, a direct comparison with our data is not possible.[36]

Head impact velocities in alpine sports

Yamazaki *et al*[39] described the head impact velocity of one real-life case of a downhill alpine skiing severe TBI. This was a high-speed crash landing after a large jump, where the athlete landed partly sideways. Yamazaki *et al*[39] reported a velocity change of 11 m/s in the normal and along-slope directions, and a frontal plane angular velocity change of 100 rad/s.[39] The angular velocity change was substantially greater than in our cases. The difference in skiing speed and the different circumstances surrounding the crashes, such as the landing variables (snow properties, size of the jump, drop height and steepness of the landing/impact slope) should be considered when comparing the results.

Although a description of head impact velocities is essential with respect to informing helmet testing standards, snow properties will influence the peak head accelerations during a crash. Although FIS WC-prepared snow is generally hard or icy, it is essential for future studies to investigate snow properties such as the liquid–water content, density and texture when reporting head impact magnitudes. In addition, the impact angle of the slope must be considered.

Scher *et al*[38] reported that during back edge catches, the peak linear accelerations on soft snow were 83 g with and 74 g without a helmet, and on hard/icy snow 162 g with and 391 g without a helmet. From qualitative video analysis, it is difficult to assess snow properties. Therefore, future laboratory or field-based studies should examine snow properties quantitatively and in detail.

Head impact velocities in other sports

We do not know the head accelerations in our four cases. Therefore it is difficult to compare our findings to acceleration measures from head impacts in other sports. Still, the head impact velocity changes we found in our four cases are comparable to velocity changes in American football (range 7.2 m/s to 9.3 m/s), where also corresponding peak linear accelerations (range 64 g to 112 g) and angular accelerations (range 4253–8022 rad/s^2) have been reported.[40–42] Viano *et al*[40] reported an angular velocity change of 34.8 ± 15.2 rad/s, which is similar to our range.[40] The velocity changes we reported are also similar to concussive head impacts in unhelmeted Australian football and rugby players, where the linear peak velocity change ranged from 3.2 to 9.3 m/s.[43]

Relevance for helmet testing standards

Of the four cases we have analysed, the new helmet rule (both EN 1077 and ASTM 2040 and additional EN 1077 test of 6.8 m/s) only applies to one case (case 2), who is a ski cross athlete. However, the freestyle ski cross case we have analysed (case 2) is from 2008 (ie, the injury occurred in 2008), which is before the new rule was implemented. None of our four cases were required to have helmets complying with the new FIS helmet rule at the time of injury. Case 4 was injured after the implementation of the new rule (during the 2013/2014 season) but belongs to a discipline where the new helmet rule has not been enforced (snowboard slopestyle).

Under current rules, only case 2 (freestyle ski cross) belongs to a discipline where the new standard has been enforced. The other cases can still comply with the original test standards (EN 1077, impact velocity 5.4 m/s or ASTM F2040, impact velocity 6.2 m/s).

The preimpact velocity, which relates most directly to the height specified in helmet drop tests, was for all of our cases higher than the prevailing requirements at the time of the incidents (5.4 m/s (EN 1077) or 6.2 m/s (ASTM F2040)) and the current FIS rule of EN 1077 plus ASTM F2040 plus 6.8 m/s impact test. Nonetheless in three of the four cases studied, which only comprise 5% (4/76) of the sample of head injury cases, the athlete's absence due to injury was less than 7 days. This suggests that the helmets worn provided substantial protection to the head against moderate to severe TBI and might exceed the homologation requirements. Homologation requirements are minimum performance requirements; for example, McIntosh and Patton[44] observed in two AS/NZS 2063-compliant bicycle helmets that the peak headform acceleration at a drop height of 2.5 m remained under the 250 g pass level for the 1.5 m requirement mandated in AS/NZS 2063.[44] The helmet models, condition and impact damage in three of our four cases is unknown. It was well documented by the media during the 2014 Olympic Winter Games in Sochi that the helmet in case 4 broke during the crash. However, we do not know the precrash condition of the helmet.

Ideally, this study would be complemented by inspection of the helmets worn and testing of exemplar helmets. The results do not provide a strong case for changing the helmet impact speeds in FIS-mandated standards for these sports and are limited by the sample size, helmet models and our understanding of the differences between real-world impacts on snow and laboratory impacts.

An impact anvil is typically rigid, which will produce a higher head acceleration compared with a real-world impact against a compliant surface such as snow/ice. Headforms used in laboratory tests are also rigid and will produce a higher head acceleration compared with a human head or equivalent headform.[39] For those reasons, when considering equivalence between real-world impacts and laboratory tests, laboratory helmet testing velocities on rigid anvils are often lower than what is observed in real-world impacts.[39]

Angular kinematics

Our findings indicate that there is a considerable angular velocity change of the head in each crash. It is important to consider the angular kinematics of the head in the causation of brain injuries.[45 46] In comparison with helmet drop tests, in which preimpact angular motion is minimal and angular motion during the impact is constrained by the test system, our results identified that, during the fall, the head had developed angular velocity preimpact and there was a greater change in angular velocity during impact. Both linear and angular velocity results demonstrated that there was a rebound phase, which might not be anticipated in an impact with soft snow. This change in head angular velocity would be reflected in head angular acceleration. The helmet and snow/ice impact interface may both contribute to rebound. Further research is required on the snow/ice impact interface. Measurements of rebound on 150 motorcycle helmets in drop tests show that the coefficient of restitution (CR) varies by helmet model and drop height.[47] For example, the average CR was 0.35 in 0.8 m drop tests compared with 0.27 in 2.5 m drop tests, where the mandated drop height in United Nations Economic Commission for Europe (UNECE) 22 (motorcycle helmets) is 2.5 m.[47] These results suggest that the selection of the foam liner properties is important and may be tuned to specific impact management requirements in standards. This issue might be addressed in a standard by (1) including a performance criteria for coefficient of restitution or (2) including an oblique impact test[27 28] to assess the ability of the helmet to manage the head's angular kinematics. The impact angles of the helmet velocity vector relative to the slope at the frame of impact were between 25° and 57°. However, in our cases, we do not have information about the snow properties, muscle activation (such as neck muscle contraction) or force transfer from the body or neck to the head at the impact, which makes the consequence of the impact angles difficult to consider. Importantly, we also do not have information about angular velocity changes in other planes of movement. Yamazaki *et al*[39] described a frontal plane angular velocity change of 100 rad/s after a high-speed sideways fall. In other words, angular velocity changes can be considerably greater than we described, and may occur in all three planes.

What are the findings?

- This is the first study to describe the gross head impact biomechanics, and to report head impact velocities of four real concussive events in International Ski Federation World Cup snowboarding and freestyle skiing.
- In all four cases, the estimated normal-to-slope preimpact velocity was higher than the prevailing helmet standards (5.4 m/s and 6.2 m/s) at the time of injury and higher than the current strictest helmet testing rule of 6.8 m/s.
- The helmets offered a high level of protection to the head.
- The head may undergo a considerable angular velocity change during the head impact which may contribute to brain injury and may be influenced by the snow/ice interface and the helmet foam liner characteristics.

How might it impact on clinical practice in the future?

- This study provides important information about real-life head impact velocities and gross head impact biomechanics in snowboarding and freestyle skiing.
- Information about real-life head impact velocities and accurate descriptions of the mechanisms of head injuries are important considerations if helmet testing is to be developed and evaluated with regard to realistic impact conditions.
- Future laboratory or field-based studies should examine snow properties quantitatively and perform helmet impact tests on real-life snow and ice.

LIMITATIONS

The study sample was derived systematically from a prospective collection of videos from a defined athlete population. This process produced only a limited number of cases with a sagittal view of the crash on video. Therefore, we cannot be certain that the injury videos are representative of head injury situations in this WC cohort. Based on previous literature from the recreational level, there is a compelling argument that the injury mechanisms analysed in this study are representative.[32 35]

Comparing our four concussive cases with similar control cases would have been helpful in identifying head impact velocities in concussions compared with in non-concussive events (controls). However, we were not able to find suitable control videos.

TV footage will typically become blurry when there are large velocity changes. Coupled with limited frame rate (25–60 Hz), this makes it challenging to estimate impact velocities accurately. However, our error assessments showed that the measurements were reasonably accurate. We attempted to optimise the accuracy by performing three trials for the linear velocity and angular velocity measures, and reporting the mean. The mean root mean square error of the digitised head position was under 2 cm, indicating that the intrarater digitising was consistent between trials. However, it remains unclear how digitisation by different persons would have influenced the outcome measures.

Also the video resolution, the athlete's pixel size in the video image as well as the visibility of landmarks in the background may influence the estimation of displacement time data from the videos. The main limitations in our velocity analyses, however, are not from the limited spatial resolution but from snow spray, camera blur and limited temporal resolution. Blur is mainly a problem in the few frames immediately after impact. Hence, it was not possible to accurately measure the kinematics during the short duration of the impact. Image quality until the last frame before impact allowed for accurate visualisation of helmet reference points and estimation of head velocity immediately before impact, as verified by the estimates of vertical acceleration during flight.

We also cannot be certain that the video footage is aligned with the true vertical axis. In response, we partly verified this by reporting the vertical acceleration and root mean square error during the flight phase. The root mean square error during the flight phase of three cases ranged between 0.47 and 1.55 m/s from the regression line, indicating a low error of our vertical velocity estimates in cases 2 and 4, while the error was higher in case 1. However, although we have error estimates for the vertical velocity, we do not know how this error translates to the normal-to-slope and along-slope velocity measures.

The estimated vertical acceleration during the flight phases of cases 1, 2 and 4 was close to the gravitational acceleration constant of 9.8 m/s^2, which indicates that the accuracy of our vertical velocity estimates was reasonable, while our horizontal error was greater. The relatively accurate results relating to the vertical acceleration measurements most likely arose because of the restrictive case inclusion and exclusion criteria. However, we do not know what is likely the cause of the discrepancy between the estimated acceleration due to gravity and the target value of 9.8 m/s^2. Possibly, this could be due to discrepancies relating to the vertical axis of the camera, digitisation error or calibration length error.

We chose not to filter the angular velocity signal, considering that this would give the most realistic estimate of the actual angular velocity. The reason is that the change in head rotation could be as high as 40° between two frames. A filter would underestimate the measured angular velocity change between two frames considerably. Therefore, some caution and interpretation are required if these angular velocity change estimates were to be compared with angular velocity measured in controlled experiments using defined signal conditioning methods.

CONCLUSION

In all four cases, the estimated normal-to-slope preimpact velocity was higher with regard to the prevailing helmet standards at the time of injury and higher than the current strictest helmet rule of 6.8 m/s. Considering this, helmets offered a high level of protection to the head: there were no skull fractures and absence due to injury was less than 7 days in three cases. The study identified a method for studying gross injury mechanisms and head kinematics that needs to be reproduced on a larger sample. The study identified that the head may undergo a considerable angular velocity change during the head impact which may contribute to brain injury and that may be influenced by the snow/ice interface and the helmet foam liner characteristics.

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Contributors All authors have made substantial contributions to all of the following: (1) the conception and design of the study, acquisition of data, and analysis and interpretation of data; (2) drafting the article or revising it critically for important intellectual content and (3) final approval of the version to be submitted.

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Competing interests None declared.

Patient consent Detail has been removed from this case description/these case descriptions to ensure anonymity. The editors and reviewers have seen the detailed information available and are satisfied that the information backs up the case the authors are making.

Ethics approval The project has been reviewed by the Regional Committee for Medical Research Ethics, South Eastern Norway Regional Health Authority, Norway, and approved by the Social Science Data Services.

Provenance and peer review Not commissioned; externally peer reviewed.

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Head impact velocities in FIS World Cup snowboarders and freestyle skiers: Do real-life impacts exceed helmet testing standards?

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Reconstruction of head impacts in FIS World Cup alpine skiing

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ABSTRACT

Introduction Prior to the 2013/2014 season, the International Ski Federation (FIS) increased the helmet testing speed from 5.4 to 6.8 m/s for alpine downhill, super-G and giant slalom. Whether this increased testing speed reflects head impact velocities in real head injury situations on snow is unclear. We therefore investigated the injury mechanisms and gross head impact biomechanics in seven real head injury situations among World Cup (WC) alpine skiers.

Methods We analysed nine head impacts from seven head injury videos from the FIS Injury Surveillance System, throughout nine WC seasons (2006–2015) in detail. We used commercial video-based motion analysis software to estimate head impact kinematics in two dimensions, including directly preimpact and postimpact, from broadcast video. The sagittal plane angular movement of the head was also measured using angle measurement software.

Results In seven of nine head impacts, the estimated normal to slope preimpact velocity was higher than the current FIS helmet rule of 6.8 m/s (mean 8.1 (±SD 0.6) m/s, range 1.9±0.8 to 12.1±0.4 m/s). The nine head impacts had a mean normal to slope velocity change of 9.3±1.0 m/s, range 5.2±1.1 to 13.5±1.3 m/s. There was a large change in sagittal plane angular velocity (mean 43.3±2.9 rad/s (range 21.2±1.5 to 64.2±3.0 rad/s)) during impact.

Conclusion The estimated normal to slope preimpact velocity was higher than the current FIS helmet rule of 6.8 m/s in seven of nine head impacts.

INTRODUCTION

Based on data from the International Ski Federation (FIS) Injury Surveillance System (ISS) at the alpine World Cup (WC) level, head injuries represent 8%–10% of all injuries that require medical attention.[1 2] These injury data cover a period during which helmet use has been mandatory in all FIS WC events.[3] However, helmets may not always offer optimal protection because of (A) intrinsic aspects of helmet performance, which are reflected in the helmet standards, (B) user error, for example, selection of a poorly fitting helmet or failure to properly fasten and secure the helmet, and (C) unique characteristics of the crash situation.

Prior to 2013/2014, alpine WC helmets had to comply with either European Standard (EN) 1077 (class A: giant slalom, super-G and downhill; class B: slalom) or American Society for Testing and Materials (ASTM) F2040 as minimum standards.[4] The EN 1077 test standard's testing pass/fail criterion is peak linear maximum acceleration of 250 g (g_{max}<250 g) in a drop test at 5.4 m/s onto a flat anvil.[5] In comparison, the pass/fail criterion for the ASTM F2040 standard is 300 g peak linear acceleration (g_{max}<300 g) in a drop test at 6.2 m/s onto a flat anvil.[6] While the EN 1077 standard only includes drop tests on a flat anvil, the ASTM F2040 standard also includes drop tests on hemispherical and hazard anvils.[5 6] Commencing prior to the 2013/2014 WC season, FIS enforced a new helmet testing rule for alpine giant slalom, super-G and downhill.[3] Under the new, stricter rule, helmets must be certified to both ASTM 2040 and EN 1077 (class A) standards. In addition, the helmets are required to pass an added specific test using the EN 1077 impact energy attenuation test method with an impact speed of 6.8 m/s, which corresponds to a drop height of 2.4 m.[4] At present, this new and stricter rule has not been enforced by FIS for slalom.[4] In slalom, the helmets have to comply with EN 1077 class B or ASTM F2040.[4]

Helmets are commonly assessed in impacts against rigid surfaces (mainly steel anvils), which are similar to roads or pavements, and not against more compliant surfaces such as snow.[7] These unyielding test surfaces are not necessarily designed only to simulate real-world conditions; they are also a prerequisite for a rugged and repeatable impact test and cause the helmet to be the primary energy attenuating object in the test system.[7] Therefore, future helmets should be developed and evaluated with regard to realistic impact conditions, including impact speed(s) and surfaces, such as snow and ice.[8]

The current direction in helmet development and testing is to consider the capacity of helmets to manage the head's angular kinematics (acceleration and/or velocity).[8–10] At present, angular kinematic management is not considered in any national or sports-specific standard, except through general construction requirements that consider surface characteristics and external projections. Therefore, it is of interest to describe angular kinematics during helmeted real-world impacts in as much detail as possible, with the data obtained from this video analysis.

The study aims were: (1) to describe the injury mechanisms in a selection of head impact injury cases meeting our inclusion criteria among WC alpine skiers, (2) to describe the gross head impact biomechanics, and (3) to compare the head impact kinematics with relevant helmet standards.

METHODS

Case selection and video processing

All cases among men and women in the FIS ISS from WC and Olympic Winter Games (OWG) competitions for the period 2006–2015 were reviewed for

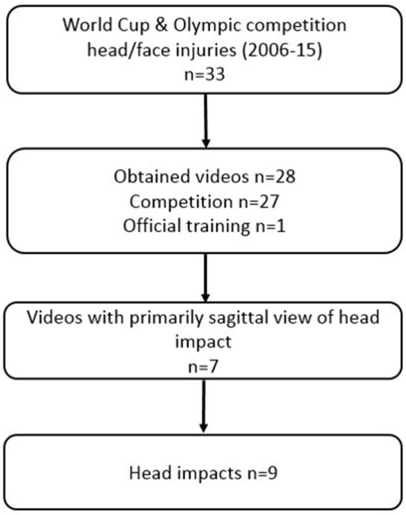

Figure 1 Flow chart of the video acquisition process.

head/face injuries.[1 2 11] This resulted in a total of 33 cases, where 27 videos were obtained and reviewed for suitability. In addition, we obtained one video from an official WC training run. In total, we therefore obtained 28 videos (figure 1).

In order to obtain valid velocity estimates, we required a primarily sagittal view of the athlete during the incident. Of the 28 videos obtained, only 7 met this criterion (figure 1).

Of the seven suitable videos, two cases had two head impacts. In the remaining cases, the athlete had one head impact, allowing us to analyse nine head impacts from seven cases.

All seven videos had an interlaced scan with frame rates of 25 and 30 Hz, making it possible to double the effective frame rates to 50 and 60 Hz. Videos were edited and deinterlaced using Adobe premiere Pro CS6 (Adobe Systems, San Jose, CA). The video display resolution was 1024×576 for cases 1 and 7; 704×480 for case 2; and 788×576 for cases 3–6.

Analysis of gross head impact injury mechanisms

The injury videos were viewed frame by frame by all authors to analyse the skiing situation and gross body biomechanics preinjury, in addition to analysing the head impact in detail. Image sequences of the injury situations and qualitative descriptions of the gross injury mechanisms were compiled based on agreement between all authors.

Linear kinematic analysis

A commercial software program for video-based movement analysis (SkillSpector, V.1.3.2, Odense, Denmark) was used to digitise a fixed point on the helmet, as well as two reference points in the surroundings. We created a local calibration frame that was oriented with axes along and normal to the slope of the surface during the head impact. We assumed that the vertical direction of the video footage was aligned with the true vertical axis. The local calibration frame was positioned at the frame of head impact using the length of the skis for scaling. The measurement of the skis was performed at the closest possible frame to the frame of impact where we could see the ski perpendicularly and in full length. In three head impacts (case 1—impact 1, case 4, case 6—impact 1), the measurement frame was the same as the calibration frame. For the remaining six head impacts, we could not see the ski perpendicularly and in full length during the head impact frame, and the measurement frame was therefore different from the calibration frame. The mean time from the measurement frame to the calibration frame for these six impacts was 0.13 s. The ski lengths ranged from 210 to 216 cm, corresponding to a range from 78 to 268 pixels (mean 172), with corresponding pixel lengths ranging from 0.4 to 1.3 cm (mean 0.8 cm). We obtained actual ski dimensions from the athlete or their ski supplier.

We used a smoothing spline algorithm with a 15 Hz cut-off to calculate the head velocity.[12] To determine the change in linear velocity in the normal to slope and along slope directions, we extracted variables from preimpact and postimpact frames, immediately before and after (maximum four frames (80 ms)) the helmet impact (figure 2). The lowest downward velocity immediately preimpact was reported, in addition to the highest upward velocity immediately postimpact (figure 2).

Error assessment

We performed three digitising trials for each case and we report the mean±SD of the three trials. As a measure of the intrarater digitising error, we calculated the root mean square error (cm) of the helmet position (normal and along slope) between the three digitising trials for all nine head impacts, and report the mean.

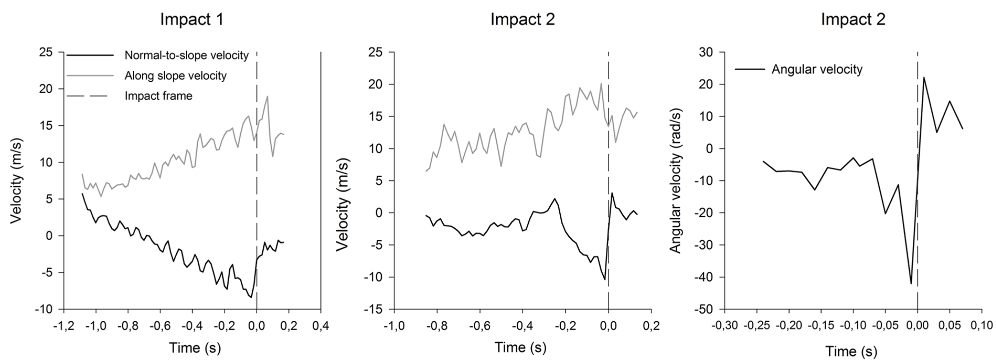

Figure 2 Case 1, impacts 1 and 2 (60 Hz). Linear velocity (m/s) of case 1, impact 1 and linear velocity (m/s) and angular velocity (rad/s) of case 1, impact 2.

Furthermore, we investigated the validity of our velocity estimates. We therefore calculated the vertical and horizontal velocities, and the acceleration of the skier's pelvis during flight, to see if it complied with the laws of physics. For these analyses, we assumed that the vertical axis of the video image was aligned with the true vertical axis. We performed three separate digitising trials of the pelvis only during the flight phases and fitted a linear regression line for the mean velocity of the pelvis for the flight phases of two cases to estimate the acceleration. For the digitisation of the pelvis, it was possible to perform the ski measurement and the calibration in the same frame. The calibration frame was aligned with the video image. The remaining cases either did not have a flight phase or had a flight phase where we did not have a sagittal view. We reported the root mean square error (m/s) from the regression line of the flight phases of the two eligible cases in both the vertical and horizontal directions.

Head impact angle

The impact angle is defined as the angle between the head velocity vector immediately prior to impact and the slope at the frame of impact.

Angular kinematic analysis

For four cases (cases 1, 2, 4 and 7), it was possible to measure the sagittal plane angular movement of the head/helmet/neck unit. We measured the sagittal plane angular velocity of the head/helmet/neck unit frame by frame, from at least 10 frames preimpact to at least five frames postimpact, using an angle measurement software (MB Ruler V.5.3, Markus Bader—MB-Softwaresolutions). We aligned the MB Ruler visually with an estimated alignment from the chin to the estimated midpoint of the top of the helmet on a frame-by-frame basis. We did three trials for each case and we reported the mean angular velocity±SD. We calculated the root mean square error of the three trials of the angular measurement.

Angular velocity was estimated as the change in angle between two frames divided by the time interval. The angular velocity data were not filtered. To estimate the change in angular velocity, we used the lowest negative point of the preimpact angular velocity and the peak of the postimpact angular velocity (maximally four frames (80 ms or less) before and after the impact) (figure 2).

Injury severity

The injury registration in the FIS ISS also covers the OWG. The FIS ISS classifies injury severity according to the duration of absence from training and competition as: slight (no absence), minimal (1–3 days), mild (4–7 days), moderate (8–28 days) and severe (>28 days).[13] This classification of injury severity is an operational injury definition within the FIS ISS (where all injuries and not only head/face injuries are registered), and therefore not a head injury specific definition of severity.

RESULTS

Case 7 complied with the new FIS helmet rule at the time of injury (ASTM F2040 (class A) and EN 1077 and additional EN 1077 test of 6.8 m/s) while cases 1 through 6 complied with the previous helmet rule (ASTM F2040 (class A) or EN 1077) (table 1). In all seven cases, the helmet was retained on the head during the crash.

In six cases, the primary diagnosis was concussion, and in one case the primary diagnosis was an ACL injury combined with a concussion (table 1).

Gross head impact injury mechanisms

With regard to injury mechanisms, in seven impacts the athletes pitched backwards (figures 3 and 4), and in two impacts the athletes pitched forward or backward in a spiralling motion (figure 5). The impact locations on the helmet were to the back of the helmet (n=5), to the top of the helmet (n=2) and to the side (n=2). Please see figures 3-5 for image sequences illustrating examples of the injury situations, and for descriptions of the gross injury mechanisms. Please see videos of the seven head impact injury cases provided in the manuscript supplementary video files 1–7.

Linear velocity

The mean normal to slope preimpact velocity of the nine head impacts was 8.1±0.6 m/s (range 1.9±0.8 to 12.1±0.4 m/s) (table 2). The nine head impacts had a mean normal to slope velocity change of 9.3±1.0 m/s (range 5.2±1.1 to 13.5±1.3 m/s) and a mean along slope velocity change of −1.3±0.7 m/s (velocity decrease), with a range from −4.2±0.7 m/s (velocity decrease) to +2.9±0.7 m/s (velocity increase) (table 2).

Angular velocity

All cases displayed sagittal plane peak head angular velocity immediately prior to impact. The mean angular velocity change was 43.3±2.9 rad/s (range 21.2±1.5 to 64.2±3.0 rad/s) (table 2).

Head impact angle

The mean angle between the head velocity vector prior to impact relative to the slope at the frame of impact was 32° (range 6°to78°).

Error assessment

It was possible to perform separate digitising trials of the pelvis during the flight phase for two cases (cases 1 and 3), where we could estimate vertical and horizontal velocities and acceleration.

Table 1 Description of the seven head impact injury cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Sex	Male	Female	Male	Male	Female	Female	Male
Diagnosis	Concussion	Concussion	ACL injury, concussion	Concussion	Concussion	Concussion	Concussion
Severity (absence)	8–28 days	4–7 days	>28 days	4–7 days	>28 days	4–7 days	>28 days
Season of injury	2009/2010	2009/2010	2008/2009	2008/2009	2006/2007	2007/2008	2014/2015*
Discipline	Super-G	Downhill	Super-G	Downhill	Downhill	Downhill	Super-G
Competition	Olympic Winter Games	Olympic Winter Games	World Cup	World Cup	World Cup	World Cup	World Cup

*Complied with new International Ski Federation (FIS) helmet rule at time of injury (ASTM F2040 (class A) and EN 1077 and additional EN 1077 test of 6.8 m/s).

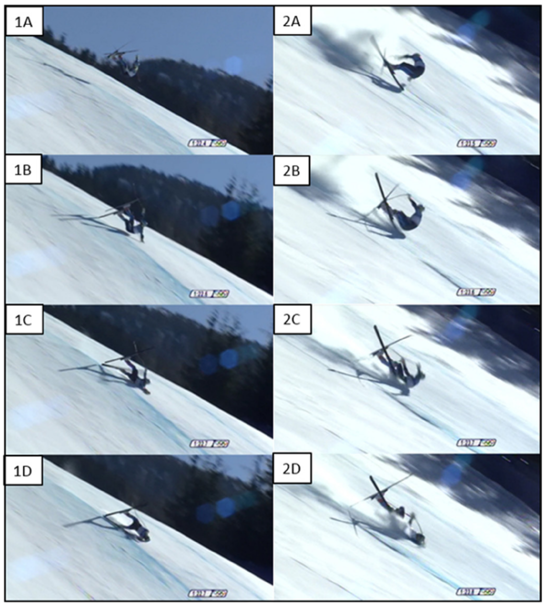

Figure 3 Case 1, impacts 1 and 2 (60 Hz). Key crash events (impact 1: 1A–D): the athlete pitches backwards and rolls sideward to the left on impact with the snow. Key crash events (impact 2: 2A–D): the athlete pitches backwards and rolls on impact with the snow.

Acceleration due to gravity is 9.81 m/s², and is therefore the target value for our vertical acceleration estimates. The vertical acceleration was 10.5 and 8.7 m/s², and the root mean square error was 0.60 and 1.4 m/s for cases 1 and 3, respectively. Our target measure for the horizontal component of the gravitational acceleration is 0 m/s². The horizontal acceleration was 0.7 and −0.2 m/s², and the root mean square error in the horizontal direction was 0.9 and 2.9 m/s for cases 1 and 3, respectively.

The mean root mean square error of the three digitising trials of the helmet position in the normal to slope direction was 2.5 cm, and in the along slope direction 3.0 cm for the nine head impacts.

The mean root mean square error of the three trials of the angular measurement of the helmet was 3°.

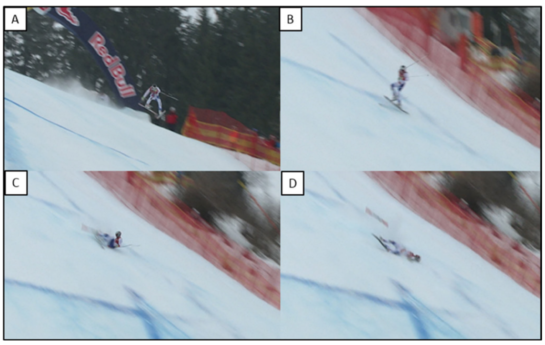

Figure 4 Case 7 (50 Hz). Key crash events (A–D): the athlete pitches backwards and rolls to the left on impact with the snow.

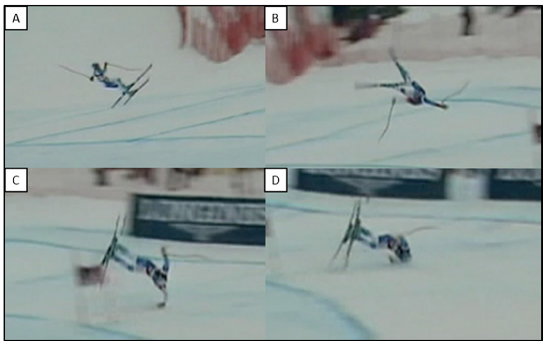

Figure 5 Case 3 (50 Hz). Key crash events (A–D): the athlete pitches forward in a spiralling motion and dives head first into the snow.

DISCUSSION

This is the first study to reconstruct a series of real-life head impact injury cases in WC alpine skiing. In seven of the nine head impacts, the estimated normal to slope preimpact velocity was greater than the prevailing minimum requirements at the time of the incidents of 5.4 m/s (EN 1077) and 6.2 m/s (ASTM F2040), and also higher than the current strictest FIS helmet testing rule of 6.8 m/s (EN 1077—additional test) for alpine giant slalom, super-G and downhill. The change in head velocity from preimpact to postimpact in the normal to slope direction ranged from 5.2±1.1 to 13.5±1.3 m/s. Only one head impact had a normal to slope preimpact velocity below the previous FIS helmet testing rule of 5.4 m/s.

Gross injury mechanisms

We identified a gross injury mechanism where the athlete pitched backward and impacted the back of the helmet in five of nine head impacts (figures 3: 2A–D and 4). This mechanism is characterised by the athlete landing onto his/her buttocks and pitching backwards onto his/her back, followed by impacting the back of the helmet (figures 3: 2A–D and 4). This is similar to a slapback mechanism in freestyle skiers[14] or a back-edge catch mechanism in snowboarders, where athletes also pitch backwards, impacting the back of the helmet.[15]

We observed two additional gross injury mechanisms, where the athletes pitched either forward or backward in spiralling motions, impacting the top part of the helmet (case 3, case 6—impact 1, figure 5) or situations where the athlete landed partly sideways, impacting the snow with the side of the helmet (case 1—impact 1, case 6—impact 2, figure 3: 1A–D).

Linear kinematics and implications for helmet standards

The normal to slope preimpact velocity, which relates most directly to the height specified in helmet drop tests, was in seven of nine helmet impacts higher than the prevailing requirements at the time of the incidents (5.4 m/s (EN 1077) or 6.2 m/s (ASTM F2040)) and the current FIS helmet rule of EN 1077 plus ASTM F2040 plus 6.8 m/s impact test.

As expected, on a low friction surface such as snow/ice, the along slope velocity change was relatively insignificant compared with the normal to slope velocity change, despite velocities of up to 28 m/s in our study.

We have only analysed 21% (7/33) of the head injury cases in this athlete population during the 2006–2015 time period, and this sample size is too small to generalise our findings. There

Table 2 Estimated linear velocity of the digitised helmet points including the change in head velocity of cases 1–7 (nine impacts), and estimated angular velocity of cases 1, 2, 4 and 7 (five impacts) ±SD of the three trials. Negative linear velocity refers to downward movement (towards the slope) in the normal to slope direction, while positive velocity refers to a rebound (upward) movement. Negative angular velocity refers to a head rotation towards extension while positive angular velocity refers to a head rotation towards flexion. A negative velocity change in the along slope direction indicates a decrease in velocity from preimpact to postimpact, while a positive along slope velocity change indicates a velocity increase

Case number	Analysed frame rate (Hz)	Preimpact velocity (±SD)	Postimpact velocity (±SD)	Change in velocity (±SD)
Normal to slope velocity (m/s)				
1—*impact 1*	60	−8.4 (0.6)	−0.9 (0.4)	7.5 (0.7)
1—*impact 2*	60	−10.4 (0.7)	3.1 (0.6)	13.5 (1.3)
2	50	−8.3 (0.4)	0.4 (0.3)	8.7 (0.1)
3	50	−1.9 (0.8)	3.3 (1.0)	5.2 (1.1)
4	50	−5.6 (0.1)	3.1 (0.1)	8.7 (0.1)
5	50	−8.2 (1.1)	0.0 (0.9)	8.2 (1.9)
6—*impact 1*	50	−7.7 (0.7)	3.5 (2.2)	11.2 (2.1)
6—*impact 2*	50	−10.1 (0.6)	−1.8 (0.3)	8.3 (1.0)
7	50	−12.1 (0.4)	0.4 (0.4)	12.5 (0.3)
Along slope velocity (m/s)				
1—*impact 1*	60	14.8 (0.7)	17.7 (0.3)	+2.9 (0.7)
1—*impact 2*	60	14.8 (0.2)	15.1 (0.4)	+0.3 (0.3)
2	50	1.9 (0.4)	0.0 (0.3)	−1.9 (0.4)
3	50	18.7 (1.1)	15.8 (0.8)	−2.9 (1.5)
4	50	27.9 (1.3)	27.4 (0.9)	−0.5 (0.6)
5	50	16.9 (0.8)	16.6 (0.3)	−0.3 (0.7)
6—*impact 1*	50	10.2 (0.1)	6.5 (0.8)	−3.7 (0.7)
6—*impact 2*	50	14.9 (0.5)	13.9 (0.7)	−1.0 (0.5)
7	50	17.6 (0.2)	13.4 (0.5)	−4.2 (0.7)
Angular velocity (rad/s)				
1—*impact 1*	60	−10.5 (3.7)	18.0 (3.2)	28.5 (3.5)
1—*impact 2*	60	−42.1 (0.5)	22.1 (2.9)	64.2 (3.0)
2	50	−42.8 (0.3)	15.8 (0.9)	58.6 (1.0)
4	50	−18.5 (1.2)	2.7 (2.1)	21.2 (1.5)
7	50	−24.3 (4.8)	19.6 (1.2)	43.9 (5.6)

were no skull fractures or severe traumatic brain injuries (TBIs) reported among our seven cases. However, in three of the seven cases, the absence due to injury was over 28 days. Importantly though, in case 3, where the athlete had the lowest estimated preimpact velocity (1.9±0.8 m/s), the athlete suffered an ACL rupture as his primary diagnosis, and the absence (>28 days) relates to his ACL injury. We do not know his concussion-related absence. We can therefore only classify two cases (cases 5 and 7) as severe concussions as defined by the FIS ISS.[1 13] In both of these cases, the normal to slope preimpact velocity was above the helmet testing velocity at the time of the injury. Case 7 obtained a severe injury with a helmet complying with the new FIS helmet rule (6.8 m/s). The preimpact velocity in this incident was 12.1±0.4 m/s. Case 5 had a helmet complying with the previous FIS helmet rule (5.4 or 6.2 m/s) and the preimpact velocity in this incident was 8.2±1.1 m/s.

The absence due to injury was 4–7 days in three cases (cases 2, 4, 6), indicating that the helmets provided adequate protection of the head in these cases. In these cases, the helmets complied with the previous helmet rule (5.4 or 6.2 m/s). The preimpact velocities in these cases ranged from 5.6 to 10.1 m/s, and were therefore above the minimum helmet test speed (5.4 m/s) at the time of the injury.

Previous reconstructive studies of head impact kinematics in snow sports have reported similar results to our findings, with normal to slope head impact velocities of 8.11, 7.8±1.7 and 11 m/s.[16–18] In line with these results, we previously reported that helmet preimpact velocities in four cases of snowboarding backedge catches and freestyle head impacts ranged from 7.0±0.2 to 10.5±0.5 m/s in the normal to slope direction, with normal to slope velocity changes ranging from 8.4±0.6 to 11.7±0.7 m/s.[19]

Our results, however, do not indicate a need to change the helmet impact velocities in FIS-mandated helmet rules in alpine skiing at present. This is partly because our study is limited by the sample size and a lack of information concerning the helmet models used. In addition, we lack information about the relationship between real-world head impacts onto snow and ice, and laboratory head impacts during helmet testing procedures. We have in a previous paper extensively discussed issues relating to the equivalence between real-world impacts and laboratory helmet tests.[19] We reiterate that the relationship between real head impacts on snow and laboratory testing on rigid anvils must be investigated further by performing helmet testing outside on real WC prepared snow and ice.

Angular kinematics and implications for helmet standards

In five of the nine situations, the skier experienced a backward pitching fall with a large change in head angular velocity (21.2±1.5 to 64.2±3.0 rad/s) during impact. This may have important implications for head injury research, since rotationally induced strain deformation on the brain tissue can cause concussive trauma.[20]

To prevent head and brain injuries, the helmet's ability to minimise rebound is important, and an optimum helmet design would reduce the rebound velocity to zero.[21] Our results identified that the head underwent high angular velocity changes during impact. Changes in head angular velocity will result in head angular acceleration. Both linear and angular velocity changes demonstrated that there was a rebound phase immediately postimpact, which might not be anticipated in an impact with soft snow.

In all of the five impacts where angular velocity could be obtained, there was an angular rebound movement, indicated by a positive angular velocity postimpact (table 2). Only in case 1—*impact 1* and case 6—*impact 2* was there no detectable linear velocity rebound movement. However, case 1—*impact 1* had substantial angular rebound, while we could not measure the angular velocity of case 6. The severity of the injuries in these cases was 8–28 days (case 1) and 4–7 days (case 6). It is, however, difficult to interpret the implications of experiencing rebound compared with no rebound in our study from such a limited amount of cases. The impact angles of the head velocity vector relative to the slope at the frame of impact were between 6° and 78°. Among the five cases where angular velocity could be estimated, we observed that the cases with the greatest impact angle seemed to have the greatest angular velocity change. In these situations, the athletes pitched backward and impacted the back of the helmet (case 1—*impact 2* and case 2).

Limitations

The study sample was derived systematically from a prospective collection of videos from a defined injured athlete population. This process produced only a limited number of cases with a sagittal view of the crash on video. Therefore, these findings could be biased, and a more comprehensive video analysis study including all alpine head injury cases from the FIS ISS in all planes of movement is needed to assess the representativeness of our nine analysed head impacts.

Angular velocity changes may occur in all three planes of movement. We are limited to estimating angular velocity change in the sagittal plane. We do not have information about snow properties, muscle activation (such as neck muscle contraction) or force transfer from the body or neck to the head at impact, which makes it difficult to consider the consequence of the impact angles.

Both the helmet and the snow impact surface may contribute to rebound. As we do not have information about the snow properties in our cases, we do not know how this influenced the rebound motion. Future helmet standards could potentially address these issues.[19]

Comparing our seven injury cases with similar control cases (videos where an athlete obtained a head impact with no diagnosed head injury) would potentially be helpful in identifying if there were any differences in the impact characteristics in injury versus non-injury cases. However, identifying suitable control videos is not possible, since we cannot be certain that the athletes did not sustain a head injury, even if no injury was recorded through the FIS ISS.

Television footage will typically become blurry when there are large velocity changes. Coupled with limited frame rates (50 and 60 Hz) and snow spray, this makes it challenging to estimate impact kinematics accurately. We attempted to optimise the accuracy by performing three digitising trials of the linear velocity and angular velocity measures and reporting the mean. The mean root mean square error of the digitised helmet position was under 3 cm, indicating that the intrarater digitising was consistent between trials.

The main limitations in our velocity analyses are from snow spray, camera blur and limited temporal resolution. Blur is mainly a problem in the few frames immediately after impact. Hence, it was not possible to accurately measure the kinematics during the short duration of the impact. Image quality until the last frame before impact allowed for accurate visualisation of helmet reference points and estimation of head velocity immediately before impact, as verified by the estimates of vertical acceleration during flight.

We also cannot be certain that the video footage is aligned with the true vertical axis. In response, we partly verified this by reporting the vertical acceleration and root mean square error during the flight phase. The root mean square error during the flight phase of cases 1 and 3 was 0.60 and 1.4 m/s from the regression line, indicating a low error of our vertical velocity estimates.

The estimated vertical acceleration during the flight phases of cases 1 and 3 was close to the gravitational acceleration constant of 9.8 m/s^2, and the estimated horizontal acceleration was close to 0.0 m/s^2, which indicates that the accuracy of our vertical and horizontal velocity estimates was reasonable. The relatively accurate results relating to the vertical acceleration measurements most likely arose because of the restrictive case inclusion and exclusion criteria.

To filter the linear velocity, we chose a 15 Hz cut-off frequency because lower frequencies would oversmooth the peak velocity estimate. Through different filtering trials, we identified that a 7 Hz cut-off could underestimate the velocity change of the impact by approximately 28% compared with a 15 Hz cut-off. On average, the 15 Hz spline filter peak velocity estimates differed from those of simple differentiation by only 3%.

We chose not to filter the angular velocity signal, considering that this would give the most realistic estimate of the actual angular velocity. Although we could have used an algorithm including more time points to estimate velocity (eg, a Butterworth or spline filter), we chose to use a simple differentiation scheme because there were large changes in head orientation between frames, which progressed towards head impact (up to 40° differences between two frames). Therefore, due to the limited temporal resolution, and with a root mean square error of only 3°, we would argue that a simple differentiation scheme will likely provide the best estimates of the true velocities, since other methods would likely underestimate the maximal velocity immediately prior to the impact. We are aware that small measurement errors could potentially generate large errors in the estimates, but the angular velocity curves, showing a steady increase in angular velocity towards impact, indicate that our estimates are realistic.

However, some caution and interpretation are required if these angular velocity change estimates were to be compared with angular velocity measured in controlled experiments using defined signal conditioning methods.

CONCLUSION

In seven of nine head impacts, the estimated normal to slope preimpact velocity was higher with regard to the prevailing FIS helmet rule at the time of injury and higher than the current strictest FIS helmet rule of 6.8 m/s. There were two severe concussions among the seven cases. However, as we do not have information about the snow properties in these incidents, it is not possible to relate our findings to laboratory helmet testing standards. We identified that the head underwent a considerable angular velocity change during the head impact combined with a rebound motion, which may contribute to brain injury. The influence of the snow impact surface and the helmet foam liner characteristics require further research in order to optimise helmet performance and athlete protection.

What are the findings?

- This is the first study to describe the gross head impact biomechanics, and to report head impact velocities of seven real concussive events among International Ski Federation (FIS) World Cup alpine skiers.
- In seven of nine head impacts, the estimated normal to slope preimpact velocity was higher than the prevailing FIS helmet rule (5.4 and 6.2 m/s) at the time of injury and higher than the current strictest FIS helmet rule of 6.8 m/s.
- The head may undergo a considerable angular velocity change during the head impact which may contribute to brain injury, and may be influenced by the snow/ice interface and the helmet foam liner characteristics.

How might it impact on clinical practice in the future?

- This study provides important information about real-life head impact velocities and gross head impact biomechanics in alpine skiing.
- Information about real-life head impact velocities and accurate descriptions of the mechanisms of head injuries are important considerations if helmet testing is to be developed and evaluated with regard to realistic impact conditions.
- Future laboratory and field-based studies should examine snow properties quantitatively and perform helmet impact tests on real-life snow and ice.

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Contributors All authors have made substantial contributions to all of the following: the conception and design of the study, or acquisition of data, or analysis and interpretation of data, drafting the article or revising it critically for important intellectual content, and final approval of the version to be submitted.

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Competing interests None declared.

Patient consent Detail has been removed from this case description/these case descriptions to ensure anonymity. The editors and reviewers have seen the detailed information available and are satisfied that the information backs up the case the authors are making.

Ethics approval The study was reviewed by the Regional Committee for Medical Research Ethics, South-Eastern Norway Regional Health Authority, Norway.

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Reconstruction of head impacts in FIS World Cup alpine skiing

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Appendices

Appendix 1

FIS Injury Surveillance System Interview form

Injury Surveillance System - Interview
FIS World Cup Alpine 2015/16
Females

Athlete Name: ______________________ Athlete : ______ Male: □ Female: □

Nation: ______________ Discipline: ______________ Trainer: ______________

Contact (e-mail/cell): ______________________ MD/PT: ______________

Comments	Date	Place	Nation	Discipline	Sex	Category	Injury
	24.10.2015	**Soelden**	AUT	Giant Slalom	L	WC	
Replaces 28.11.2015	27.11.2015	**Aspen, CO**	USA	Giant Slalom	L	WC	
Replaces Levi 14.11.2015	28.11.2015	**Aspen, CO**	USA	Slalom	L	WC	
	29.11.2015	**Aspen, CO**	USA	Slalom	L	WC	
Cancelled	01.12.2015	**Lake Louise**	CAN	Downhill training	L	TRA	
	02.12.2015	**Lake Louise**	CAN	Downhill training	L	TRA	
	03.12.2015	**Lake Louise**	CAN	Downhill training	L	TRA	
	04.12.2015	**Lake Louise**	CAN	Downhill	L	WC	
	05.12.2015	**Lake Louise**	CAN	Downhill	L	WC	
	06.12.2015	**Lake Louise**	CAN	Super G	L	WC	
	12.12.2015	**Are**	SWE	Giant Slalom	L	WC	
	13.12.2015	**Are**	SWE	Slalom	L	WC	
	16.12.2015	**Val d'Isère**	FRA	Downhill training	L	TRA	
	17.12.2015	**Val d'Isère**	FRA	Downhill training	L	TRA	
	18.12.2015	**Val d'Isère**	FRA	Alpine combined	L	WC	
	18.12.2015	**Val d'Isère**	FRA	Downhill	L	COM	
	19.12.2015	**Val d'Isère**	FRA	Downhill	L	WC	
	20.12.2015	**Courchevel**	FRA	Giant Slalom	L	WC	
	28.12.2015	**Lienz**	AUT	Giant Slalom	L	WC	
	29.12.2015	**Lienz**	AUT	Slalom	L	WC	
Cancelled	01.01.2016	**Muenchen**	GER	City Event	L	WC	
Replaces Zagreb 03.01.2016	05.01.2016	**Santa Caterina Valfurva**	ITA	Slalom	L	WC	
						WC	
Replaces St. Anton	07.01.2016	**Altenmarkt-Zauchensee**	AUT	Downhill training	L	TRA	
Replaces St. Anton	08.01.2016	**Altenmarkt-Zauchensee**	AUT	Downhill training	L	TRA	
Repl. St. Anton-new:Sprint DH	09.01.2016	**Altenmarkt-Zauchensee**	AUT	Downhill	L	WC	
Replaces St. Anton	10.01.2016	**Altenmarkt-Zauchensee**	AUT	Super G	L	WC	
	12.01.2016	**Flachau**	AUT	Slalom	L	WC	
Repl. Ofterschwang 17.01.2016	15.01.2016	**Flachau**	AUT	Slalom	L	WC	
Repl. Oferschwang 16.01.2016	17.01.2016	**Flachau**	AUT	Giant Slalom	L	WC	
	21.01.2016	**Cortina d'Ampezzo**	ITA	Downhill training	L	TRA	
	22.01.2016	**Cortina d'Ampezzo**	ITA	Downhill training	L	TRA	
	23.01.2016	**Cortina d'Ampezzo**	ITA	Downhill	L	WC	
	24.01.2016	**Cortina d'Ampezzo**	ITA	Super G	L	WC	
	30.01.2016	**Maribor**	SLO	Giant Slalom	L	WC	
	04.02.2016	**Garmisch Partenkirchen**	GER	Downhill training	L	TRA	
Cancelled	05.02.2016	**Garmisch Partenkirchen**	GER	Downhill training	L	TRA	
	06.02.2016	**Garmisch Partenkirchen**	GER	Downhill	L	WC	
	07.02.2016	**Garmisch Partenkirchen**	GER	Super G	L	WC	

	11.02.2016	**Crans Montana**	SUI	Downhill training	L	TRA	
	12.02.2016	**Crans Montana**	SUI	Downhill training	L	TRA	
Cancelled	14.02.2016	**Crans Montana**	SUI	Downhill	L	COM	
Cancelled	14.02.2016	**Crans Montana**	SUI	Alpine combined	L	WC	
Replaces: Maribor	15.02.2016	**Crans Montana**	SUI	Slalom	L	WC	
	17.02.2016	**La Thuile**	ITA	Downhill training	L	TRA	
	18.02.2016	**La Thuile**	ITA	Downhill training	L	TRA	
Replaces: Crans Montana	19.02.2016	**La Thuile**	ITA	Downhill	L	WC	
	20.02.2016	**La Thuile**	ITA	Downhill	L	WC	
	21.02.2016	**La Thuile**	ITA	Super G	L	WC	
					M		
	23.02.2016	**Stockholm**	SWE	City Event	M	WC	
	23.02.2016	**Stockholm**	SWE	City Event	L	WC	
	27.02.2016	**Soldeu- El Tarter**	AND	Super G	L	WC	
	28.02.2016	**Soldeu- El Tarter**	AND	Alpine combined	L	WC	
	28.02.2016	**Soldeu- El Tarter**	AND	Super G	L	COM	
	05.03.2016	**Jasna**	SVK	Giant Slalom	L	WC	
	06.03.2016	**Jasna**	SVK	Slalom	L	WC	
	12.03.2016	**Lenzerheide**	SUI	Super G	L	WC	
	13.03.2016	**Lenzerheide**	SUI	Super G	L	COM	
	13.03.2016	**Lenzerheide**	SUI	Alpine combined	L	WC	
	14.03.2016	**St. Moritz**	SUI	Downhill training	L	TRA	
	15.03.2016	**St. Moritz**	SUI	Downhill training	L	TRA	
	16.03.2016	**St. Moritz**	SUI	Downhill	L	WC	
	17.03.2016	**St. Moritz**	SUI	Super G	L	WC	
	18.03.2016	**St. Moritz**	SUI	Team	A	NGP	
	19.03.2016	**St. Moritz**	SUI	Slalom	L	WC	
	20.03.2016	**St. Moritz**	SUI	Giant Slalom	L	WC	

Number of injuries: ________________ Number of injury forms: ________________

☐ The athlete has read and understood the Athlete Information form and consents to participate in the FIS Injury Surveillance System

____

Athlete signature

Appendix 2

FIS Injury Surveillance System injury form

Injury Surveillance Study - World Cup Teams Interview

FIS PARTNER FIS INJURY SURVEILLANCE SYSTEM

Oslo Sports Trauma RESEARCH CENTER

Injury report / *Verletzungsmeldung / Rapport de blessure*

Athlete information/
Informationen zum Athleten/Donnèes sur l'athleète

Name/ *Name/Nom:* ☐

Country/ *Land/Pays*: ☐☐☐

Gender/ *Geschlecht/ Sexe:*
- ☐ Male/ *Mann/Homme*
- ☐ Female/ *Frau/Femme*

Injury information/
Information zur Verletzung/Information sur la blessure

Discipline: ☐

Injury 1 Date of injury: ☐

Body part injured/ *Verletzter Köperteil/Partie du corps blessée:*
- ☐ Head-face/ *Kopf-Gesicht/Tête-Face*
- ☐ Neck-cervical spine/ *Nacken-Halswirbel/Nuque-Vertèbre cervicale*
- ☐ Shoulder-clavicula/ *Schulter-Schlüsselbein/Epaule-Clavicule*
- ☐ Upper arm/ *Oberarm/Bras*
- ☐ Elbow/ *Ellbogen/Coudes*
- ☐ Forearm/ *Unterarm/Avant-bras*
- ☐ Wrist/ *Handgelenk/Poignet*
- ☐ Hand-finger-thumb/ *Hand-Finger-Daumen/Main-Doigt-Pouce*
- ☐ Chest (sternum-ribs-upper back)/ *Brustkasten (Brustbein-Rippen-Brustwirbelsäule)/Thorax (Sternum-Côtes-Haut du dos)*
- ☐ Abdomen/ *Bauch/Abdomen*
- ☐ Lower back-pelvis-sacrum/ *Lendenwirbelsäule-Becken-Kreuzbein/Bas du dos-Pelvis-Sacrum*
- ☐ Hip-groin/ *Hüfte-Leiste/Hanche-Aine*
- ☐ Thigh/ *Oberschenkel/Cuisse*
- ☐ Knee/ *Knie/Genoux*
- ☐ Lower leg-Achilles tendon/ *Unterschenkel-Achillessehne/Jambe-Tendon d'Achille*
- ☐ Ankle/ *Fussgelenk/Cheville*
- ☐ Foot-heel-toe/ *Fuss-Ferse-Zehen/Pied-Talon-Orteils*
- ☐ Information not available/ *Information nicht verfügbar/Information non disponible*

Did you use any protection?
- ☐ Helmet
- ☐ Back/ *Wirbelsäule/Dos*
- ☐ Shoulder/ *Schylter/Epaule*
- ☐ Elbow/ *Ellbogen/Coudes*
- ☐ Wrist/ *Handgelen/Poignet*
- ☐ Hip-pants
- ☐ Knee/ *Knie/Genoux*
- ☐ Leg-shin
- ☐ Teeth
- ☐ Pole-protection
- ☐ Jacket with different protection
- ☐ Other

Circumstances*:*
- ☐ FIS World Cup/World Championship(WCS)
- ☐ Other FIS competition
- ☐ Other competition
- ☐ Official FIS WC/WCS training
- ☐ Official FIS training
- ☐ Other training activity on snow
- ☐ Basic training, not on snow (weight lifting, running etc.)

Injury type/ *Art der Verletzung/Genre de la blessure:*
- ☐ Fractures and bone stress/ *Frakturen und Ermüdungsbrüche/Fracture et fracture de fatigue*
- ☐ Joint (non-bone) and ligament/ *Gelenke (nicht Knochen) und Bänder/Joint (articulation) et ligament*
- ☐ Muscle and tendon/ *Muskel und Sehnen/Muscle et tendon*
- ☐ Contusions/ *Quetschungen/Contusions*
- ☐ Laceration and skin lesion/ *Fleischwunden und Hautverletzung/Plaie et lésion de la peau*
- ☐ Nervous system including concussion/ *Nervensystem inkl. Gehirnerschütterung/Système nerveux y compris commotion cérébrale*
- ☐ Other/ *Andere/Autres*
- ☐ Information not available/ *Information nicht verfügbar/Information non disponible*

Absence from training and competition/ *Abwesenheit von Training und Wettkämpfen/Absence à l'entrainement et en compétitions:*
- ☐ No absence/ *Keine Absenz/Pas d'absence*
- ☐ 1 to 3 days/ *1 bis 3 Tage/1 à 3 jours*
- ☐ 4 to 7 days/ *4 bis 7 Tage/4 à 7 jours*
- ☐ 8 to 28 days/ *8 bis 28 Tage/8 à 28 jours*
- ☐ >28 days/ *>28 Tage/>28 jours*
- ☐ Information not available/ *Information nicht verfügbar/Information non disponible*

Side/ *Seite/Part*:
- ☐ Right/ *Rechts/Droite*
- ☐ Left/ *Links/Gauche*
- ☐ Not applicable/ *Nicht anwendbar/Non applicable*

Specific diagnosis/ *Genaue Diagnose/Diagnostic spécifique:*

☐

Please complete page 2/ *Bitte vervollständigen Sie Seite 2/Svp remplir page 2*

Injury information/

Information zur Verletzung/Information sur la blessure

Injury 2

Discipline:

Date of injury:

Circumstances:

- FIS World Cup/World Championship(WCS)
- Other FIS competition
- Other competition
- Official FIS WC/WCS training
- Official FIS training
- Other training activity on snow
- Basic training, not on snow (weight lifting, running etc.)

Body part injured/ *Verletzter Köperteil/Partie du corps blessée:*

- Head-face/ *Kopf-Gesicht/Tête-Face*
- Neck-cervical spine/ *Nacken-Halswirbel/Nuque-Vertèbre cervicale*
- Shoulder-clavicula/ *Schulter-Schlüsselbein/Epaule-Clavicule*
- Upper arm/ *Oberarm/Bras*
- Elbow/ *Ellbogen/Coudes*
- Forearm/ *Unterarm/Avant-bras*
- Wrist/ *Handgelenk/Poignet*
- Hand-finger-thumb/ *Hand-Finger-Daumen/Main-Doigt-Pouce*
- Chest (sternum-ribs-upper back)/ *Brustkasten (Brustbein-Rippen-Brustwirbelsäule)/Thorax (Sternum-Côtes-Haut du dos)*
- Abdomen/ *Bauch/Abdomen*
- Lower back-pelvis-sacrum/ *Lendenwirbelsäule-Becken-Kreuzbein/Bas du dos-Pelvis-Sacrum*
- Hip-groin/ *Hüfte-Leiste/Hanche-Aine*
- Thigh/ *Oberschenkel/Cuisse*
- Knee/ *Knie/Genoux*
- Lower leg-Achilles tendon/ *Unterschenkel-Achillessehne/Jambe-Tendon d'Achille*
- Ankle/ *Fussgelenk/Cheville*
- Foot-heel-toe/ *Fuss-Ferse-Zehen/Pied-Talon-Orteils*
- Information not available/ *Information nicht verfügbar/Information non disponible*

Injury type/ *Art der Verletzung/Genre de la blessure:*

- Fractures and bone stress/ *Frakturen und Ermüdungsbrüche/Fracture et fracture de fatigue*
- Joint (non-bone) and ligament/ *Gelenke (nicht Knochen) und Bänder/Joint (articulation) et ligament*
- Muscle and tendon/ *Muskel und Sehnen/Muscle et tendon*
- Contusions/ *Quetschungen/Contusions*
- Laceration and skin lesion/ *Fleischwunden und Hautverletzung/Plaie et lésion de la peau*
- Nervous system including concussion/ *Nervensystem inkl. Gehirnerschütterung/Système nerveux y compris commotion cérébrale*
- Other/ *Andere/Autres*
- Information not available/ *Information nicht verfügbar/Information non disponible*

Absence from training and competition/ *Abwesenheit von Training und Wettkämpfen/Absence à l'entrainement et en compétitions:*

- No absence/ Keine Absenz/Pas d'absence
- 1 to 3 days/ 1 bis 3 Tage/1 à 3 jours
- 4 to 7 days/ 4 bis 7 Tage/4 à 7 jours
- 8 to 28 days/ 8 bis 28 Tage/8 à 28 jours
- >28 days/ >28 Tage/>28 jours
- Information not available/ *Information nicht verfügbar/Information* non *disponible*

Side/ Seite/Part:

- Right/ *Rechts/Droite*
- Left/ *Links/Gauche*
- Not applicable/ *Nicht anwendbar/Non applicable*

Did you use any protection?

- Helmet
- Back/ *Wirbelsäule/Dos*
- Shoulder/ *Schylter/Epaule*
- Elbow/ *Ellbogen/Coudes*
- Wrist/ *Handgelen/Poignet*
- Hip-pants
- Knee/ *Knie/Genoux*
- Leg-shin
- Teeth
- Pole-protection
- Jacket with different protection
- Other

Specific diagnosis/ *Genaue Diagnose/Diagnostic spécifique:*

Appendix 3

Video analysis form, Paper II

Oslo Sports Trauma
RESEARCH CENTER

FIS PARTNER
FIS INJURY SURVEILLANCE SYSTEM

Video analysis of head injuries in WC snowboarding, freestyle skiing and alpine skiing

Analyst: ____________________ Date: ____________________

Injury information

Injury nr:

Specific diagnosis: ____________________

Male: ________

Female: ________

Competition: ____________________

Official training: ____________________

Discipline:

Alpine:

- Downhill ____________
- Super-G ____________
- Giant slalom ____________
- Slalom ____________

Freestyle:

- Ski cross ____________
- Half pipe ____________
- Moguls ____________
- Big air ____________
- Slopestyle ____________
- Aerials ____________

Snowboard:

- Snowboard cross: ____________
- Parallel ____________
- Half pipe ____________
- Big air ____________
- Slopestyle ____________

Rider stance
- *Regular* ☐
- *Goofy* ☐

For analyst:

How many visible head impacts are there

- 0 ☐
- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- Unsure ☐
- Not visible ☐

Which head impact is the **main impact**
(if several main impacts, rank order:
#1 = first main impact)

- 0 ☐
- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- Unsure ☐
- Not visible ☐

At which frame number(s) do(es) the **main** head impact(s) occur:

	Live	***Replay (slow motion)***
1st main impact- Frame number:		
2nd main impact -Frame number:		

THE FOLLOWING QUESTIONS RELATE TO THE MAIN HEAD IMPACT(S) ONLY

1. Athlete situation preceding head impact:

i.e. the event(s) leading to the crash/injury situation

Alpine

Prior to head impact the athlete is:
- Turning ☐
- Gliding/straight skiing ☐
- Traversing ☐
- On bumps ☐
- In a compression ☐
- Approaching jump ☐
- Jumping - take off ☐
- Landing after jump ☐
- Has already crashed/fallen ☐

The athlete then:
- Falls/crashes ☐
- Does not fall ☐

If fall/crash:

Before crashing, the skier is:
- Out of balance backward ☐
- Out of balance forward ☐
- In balance in the sagittal plane ☐
- Unsure ☐

- Out of balance to the right/left ☐
- In balance in the frontal plane ☐
- Unsure ☐

- Out of balance in the transverse plane (yawing) ☐
- In balance in the transverse plane ☐
- Unsure ☐

Freestyle

Prior to head impact the athlete is:
- Turning ☐
- Bank turning ☐
- Gliding/straight skiing ☐
- Traversing ☐
- On bumps ☐
- In a compression ☐
- Approaching jump/element ☐
- Jumping - take off ☐
- Landing after jump ☐
- In between elements ☐
- Has already crashed/fallen ☐

The athlete then:
- Falls/crashes ☐
- Does not fall ☐

If fall/crash:

Before crashing, the skier is:
- Out of balance backward ☐
- Out of balance forward ☐
- In balance in the sagittal plane ☐
- Unsure ☐

- Out of balance to the right/left ☐
- In balance in the frontal plane ☐
- Unsure ☐

- Out of balance in the transverse plane (yawing) ☐
- In balance in the transverse plane ☐
- Unsure ☐

Snowboard

Prior to head impact the athlete is:
- Turning ☐
- Bank turning ☐
- Gliding/straight riding ☐
- Traversing ☐
- On bumps ☐
- In a compression ☐
- Approaching jump/element ☐
- Jumping - take off ☐
- Landing after jump ☐
- In between elements ☐
- Has already crashed/fallen ☐

The athlete then:
- Falls/crashes ☐
- Does not fall ☐

If fall/crash:

Before crashing, the athlete is:
- Out of balance backward ☐
- Out of balance forward ☐
- In balance in the sagital plane ☐
- Unsure ☐

- Out of balance to the right/left ☐
- In balance in the frontal plane ☐
- Unsure ☐

- Out of balance in the transverse plane (yawing) ☐
- In balance in the transverse plane ☐
- Unsure ☐

Did the athlete catch an edge prior to falling:
- Yes ☐
- No ☐
- Unsure ☐

If yes, which edge:
- Front edge ☐
- Back edge ☐

All disciplines - if a fall/crash is the cause of the head impact:

Body rotation preceding head impact (can choose several):
- Body rotation around perpendicular axis (yaw) ☐
- Body rotation around longitudinal axis (roll) ☐
- Body rotation around lateral axis (pitch) ☐
- None ☐
- Not visible ☐

Body rotation preceding head impact is:
- Minor (<90 deg. in any direction) ☐
- Moderate (90 to 180 deg. in any direction) ☐
- Substantial (>180 deg. in any direction) ☐

Description of the crash circumstances:
- Forward fall ☐
- Backward fall ☐
- Sideways fall ☐
- Collision ☐
- Other ☐
- Not visible ☐

All disciplines:

Prior to crashing, the athlete has inappropriate gate contact:

No	☐
Yes	☐

Yes, and cause of injury:

Yes	☐
No	☐
Unsure	☐

Prior to crashing, the athlete makes a technical error:

Yes	☐
No	☐
Unsure	☐
Not visible	☐

If yes, the error is caused by a personal mistake (technical/tactical)

Yes	☐
No	☐
Unsure	☐
Not visible	☐

If yes, the error is caused by another athlete (e.g opponent contact in SBX/SX):

Yes	☐
No	☐
Unsure	☐
Not visible	☐

If yes, the error is caused by other factors:
Please specify:

Crash situation at frame of impact

The slope in relation to the helmet at the frame of impact is:

Downward slope	☐	
Upward slope	☐	
Flat	☐	
Not visible	☐	
Other	☐	Specify: ____________

2. Description of main head impact

Does the helmet impact an object or surface other than snow (eg. gate panel, advertising board, another person, a tree etc.)	Yes	☐	If yes, which object: ____________		
	No	☐			
	Not visible	☐			
Does the helmet impact on snow	Yes	☐			
	No	☐			
	Not visible	☐			
Where is the impact location on the helmet	Top	☐			
	Back	☐			
	Side	☐	If side:	Left	☐
	Front	☐		Right	☐
	Face	☐			
	Unsure	☐			
	Not visible	☐			
Does helmet slide along surface post- impact	Yes	☐			
	No	☐			
	Unsure	☐			
	Not visible	☐			
Does helmet fall off	Yes	☐			
	No	☐			
	Not visible	☐			
Does chin strap release	Yes	☐			
	No	☐			
	Unsure	☐			
	Not visible	☐			

3. Crash circumstances

Please rank order of skis/board and bodyparts` contact with surface during landing and crash sequence until main helmet contact (1,2,3,4 etc):
#1 = first contact to snow

- Skis/board ☐
- Head/helmet ☐
- Neck ☐
- Face ☐
- Trunk/chest ☐
- Back ☐
- Buttocks/pelvis ☐
- Upper extremity ☐
- Lower extremity ☐
- Unsure ☐

4. Post-impact: security net contact

Security net

Does the athlete hit the security net? :
- Yes ☐
- No ☐

If yes: type of net
- A net ☐
- B net ☐
- C net ☐

If yes: did the security net function adequately
- Yes ☐
- No, please describe ____________________

Was the security net correctly placed?:
- Yes ☐
- No ☐
- Unsure ☐

5. Please describe the injury mechanism in your own words

Appendix 4

Detailed information about disciplines and medical information, Paper II

Appendix 4. Information about season of injury, sex, age at time of injury, discipline, injury type, diagnosis and severity (absence) of the 57 analysed head impact injury cases. Abbrevitations: Alpine: SG: super-G, DH: downhill, GS: giant slalom, SL: slalom, SGSC: super-G part of super combined competition, Freestyle: SX: ski cross, AE: aerials, HP: halfpipe, SS: ski slopestyle, Snowboard: SBX: snowboard cross, SBS: snowboard slopestyle.

ALPINE

SEASON	SEX	AGE	CATEGORY	DISCIPLINE	INJURY TYPE	ABSENCE	DIAGNOSIS
2006/07	Male	29	WC	SG	Nervous system including Concussion	1 to 3 days	Concussion
2006/07	Male	22	WC	DH	Laceration and skin lesion	8 to 28 days	Skin laceration face
2006/07	Female	21	WC	DH	Nervous system including Concussion	> 28 days	Concussion
2006/07	Male	34	WC	DH	Nervous system including concussion	> 28 days	Concussion
2007/08	Female	20	WC	DH	Nervous system including Concussion	4 to 7 days	Concussion
2007/08	Female	24	WC	SG	Nervous system including Concussion	> 28 days	Concussion
2007/08	Male	27	WC	SG	Fractures and bone stress	> 28 days	Crus fracture + concussion
2007/08	Male	30	WC	DH	Nervous system including concussion	No info.	Concussion
2008/09	Female	25	WC	DH	Nervous system including Concussion	4 to 7 days	Concussion
2008/09	Male	39	WC	DH	Nervous system including Concussion	4 to 7 days	Concussion
2008/09	Male	27	WC	SG	Joint (non-bone) and ligament*	> 28 days	Anterior cruciate ligament total tear + concussion
2008/09	Male	30	WC	GS	Nervous system including concussion	No info.	Concussion
2009/10	Female	19	WC	SL	Fractures and bone stress	8 to 28 days	Cranial trauma, Concussion
2009/10	Female	20	WC	SG	Laceration and skin lesion	1 to 3 days	Skin laceration

2009/10	Female	24	OWG	DH	Nervous system including Concussion	4 to 7 days	Concussion
2009/10	Male	40	OWG	SG	Nervous system including Concussion	8 to 28 days	Concussion, laceration face
2010/11	Male	25	WC	DH	Nervous system including Concussion	> 28 days	Concussion
2010/11	Male	41	WC	DH	Nervous system including Concussion	8 to 28 days	Concussion
2010/11	Male	29	TRA	DH	Nervous system including Concussion	> 28 days	Concussion ++ (fracture back x 2, lung collapse, fracture ribs)
2010/11	Female	24	WC	DH	Nervous system including Concussion	8 to 28 days	Concussion
2011/12	Male	26	WC	SG	Nervous system including Concussion	> 28 days	Concussion
2012/13	Male	24	WC	SG	Fractures and bone stress	> 28 days	Nose fracture + broken teeth
2012/13	Male	23	WC	SG	Nervous system including Concussion	> 28 days	Concussion
2012/13	Female	25	WC	SL	Contusions	No info.	Contusion head
2014/15	Male	27	WC	DH	Nervous system including Concussion	8 to 28 days	Concussion
2014/15	Female	24	WC	DH	Nervous system including Concussion	> 28 days	Concussion
2014/15	Female	33	WC	SG	Fractures and bone stress	8 to 28 days	Jaw fracture + knocked out teeth
2014/15	Male	26	WC	SGSC	Nervous system including concussion	> 28 days	Concussion
2015/16	Male	25	WC	GS	Other injury type	No absence	Possible concussion

FREESTYLE

SEASON	SEX	AGE	CATEGORY	DISCIPLINE	INJURY TYPE	ABSENCE	DIAGNOSIS
2007/08	Male	18	WC	SX	Nervous system including Concussion	4 to 7 days	Concussion
2008/09	Female	24	WC	SX	Nervous system including Concussion	8 to 28 days	Concussion
2009/10	Male	24	WC	SX	Contusions	4 to 7 days	Unknown
2009/10	Male	26	WC	SX	Laceration and skin lesion	4 to 7 days	Cut in the lip

2009/10	Female	17	WC	SX	Nervous system including Concussion	No info.	Concussion
2010/11	Female	17	WC	AE	Nervous system including Concussion	4 to 7 days	Concussion
2010/11	Female	21	WC	SX	Fractures and bone stress	1 to 3 days	Fractured nose
2010/11	Male	24	WC	SX	Nervous system including Concussion	> 28 days	Concussion
2011/12	Male	25	WC	AE	Other injury type	No absence	Chin + teeth injury
2012/13	Male	21	WC	HP	Nervous system including Concussion	4 to 7 days	Concussion
2012/13	Female	22	WC	SX	Nervous system including Concussion	8 to 28 days	Concussion
2012/13	Female	24	WC	SX	Nervous system including Concussion	No absence	Concussion
2012/13	Male	23	WC	SX	Nervous system including Concussion	8 to 28 days	Concussion
2015/16	Male	26	WC	AE	Fractures and bone stress	> 28 days	Fractured orbital floor
2013/14	Female	20	OWG	SS	Contusion/haematoma/bruise	No absence	Contusion

SNOWBOARD

SEASON	SEX	AGE	CATEGORY	DISCIPLINE	INJURY TYPE	ABSENCE	DIAGNOSIS
2007/08	Female	19	WC	SBX	Nervous system including Concussion	4 to 7 days	Concussion
2007/08	Female	30	WC	SBX	Nervous system including Concussion	8 to 28 days	Concussion
2008/09	Male	23	WC	SBX	Nervous system including Concussion	4 to 7 days	Concussion
2010/11	Female	21	WC	SBX	Nervous system including Concussion	8 to 28 days	Concussion
2011/12	Male	22	WC	SBX	Nervous system including Concussion	8 to 28 days	Concussion + Capsular problem right ankle
2013/14	Male	22	WC	SBX	Contusions	No absence	Head contusion

2013/14	Male	25	WC	SBX	Contusions	No absence	Unknown
2013/14	Male	22	WC	SBX	Contusions	No absence	Head contusion
2015/16	Female	26	WC	SBX	Nervous system including Concussion	8 to 28 days	Concussion
2015/16	Male	25	WC	SBX	Nervous system including Concussion	1 to 3 days	Concussion
2013/14	Female	27	OWG	SBX	Nervous system including concussion	8 to 28 days	Concussion
2013/14	Female	22	OWG	SBX	Concussion	4 to 7 days	Concussion
2013/14	Female	24	OWG	SBS	Concussion	No absence	Concussion

Ethics

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Dato: 12.10.06
Deres ref.:
Vår ref.: S-06356b

S-06356b Overvåking av skiskader på elitenivå - FIS Injury Surveillance System

Komiteen behandlet søknaden i sitt møte torsdag 05.10.06

Prosjektet oppfattes som en kvalitetssikring av FIS' skadeovervåkingssystem (ISS). Søknaden omfattes derfor ikke av komiteens mandat om fremleggelsesplikt.

Med vennlig hilsen

Tor Norseth
Leder

Julianne Krohn-Hansen
Sekretær

Kopi: Stipendiat Tonje Wåle Flørenes, Senter for idrettskadeforskning, Norges Idrettshøgskole, Pb. 4014 Ullevål Stadion, 0806 Oslo

Sophie E. Steenstrup // Head injuries in FIS World Cup alpine skiers, snowboarders and freestyle skiers