Yamazaki, Junya & Gilgien, Matthias & Kleiven, Svein & Mcintosh, Andrew & Nachbauer, Werner & Müller, Erich & Bere, Tone & Bahr, Roald & Krosshaug, Tron. (2014). Analysis of a Severe Head Injury in World Cup Alpine Skiing: A Case Report. Medicine and science in sports and exercise. 47.

https://doi.org/10.1249/mss.0000000000000511

Yamazaki, J., Gilgien, M., Kleiven, S., McIntosh, A. S., Nachbauer, W., Müller, E. … Krosshaug, T. (2015). Analysis of a severe head injury in world cup alpine skiing. *Medicine & Science in Sports & Exercise, 47*, 1113-1118.

Analysis of a Severe Head Injury in World Cup Alpine Skiing

A case report

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Running title

Analysis of a Head Injury in Alpine Skiing

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Disclosure of funding

The Oslo Sports Trauma Research Center has been established at the Norwegian School of Sport Sciences through generous grants from the Royal Norwegian Ministry of Culture, the South-Eastern Norway Regional Health Authority, the International Olympic Committee, the Norwegian Olympic Committee & Confederation of Sport, and Norsk Tipping AS.

Abstract

Traumatic brain injury (TBI) is the leading cause of death in alpine skiing. It has been found that helmet use can reduce the incidence of head injuries between 15% and 60%. However, knowledge on optimal helmet performance criteria in World Cup alpine skiing is currently limited due to lack of biomechanical data from real crash situations.

Purpose： This study aimed to estimate impact velocities in a severe TBI case in World Cup alpine skiing.

Methods：Video sequences from a TBI case in World Cup alpine skiing were analyzed using a Model-Based Image Matching (MBIM) technique. Video sequences from four camera views were obtained in full high definition (1080p) format. A 3D model of the course was built based on accurate measurements of piste landmarks and matched to the background video footage using the animation software Poser 4. A trunk-neck-head model was utilized for tracking the skier's trajectory.

Results：Immediately before head impact, the downward velocity component 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.

Conclusion：A unique combination of HD video footage and accurate measurements of landmarks in the slope made possible a high quality analysis of head impact velocity in a severe TBI case. The estimates can provide crucial information on how to prevent TBI through helmet performance criteria and design.

Key words

Traumatic brain injury, Skiing injury, Alpine skiing, Helmet, Biomechanics, Model-Based Image Matching technique

Introduction

Paragraph Number 1 Alpine skiing is a popular winter sport worldwide, enjoyed by recreational skiers as well as elite ski racers. Skiers have to plan and control their speed and trajectory in consideration for their technical skills and the environment (slope, snow, visibility, other skiers, etc.). However, it is well known that alpine skiing is associated with a risk of injury.

Paragraph Number 2 In recreational skiing, head injuries account for 17 to 19% of all injuries (4,7,19,24) and head injury appears to be the most frequent reason for hospital admission in this skiing population (1,7,21). It has been reported that head injuries mainly occur as a result of collisions with: the snow surface, other skiers, or vertical structures, such as trees and stanchions, in the natural and built environments (1,14). In competitive skiing, 8 to 10% of all injuries are to the head and face. This includes concussion, the most frequent specific diagnosis, as well as more severe forms of traumatic brain injury (TBI) such as intracranial hemorrhages (2.6.25). There have also been fatalities in WC skiing and snowboarding in the recent past (23).

Paragraph Number 3 There is epidemiological evidence showing that helmets reduce the risk of head injury in alpine skiing. A meta-analysis, based on 12 studies of recreational skiers and snowboarders reported that the risk of head injury was reduced by 35% with helmet use (22). This study did not detect any significant association between helmet use and risk of neck injury and also suggested there was no relation between helmet use and risk taking behavior (12).

Paragraph Number 4 The typical speed for recreational adult skiers is about 11–14 m/s, while in competitive skiing speed disciplines the athletes reach maximal speed of 40 m/s. The average speed varies according to the alpine disciplines (Mean ± SD: downhill 25.6 ± 4.3 m/s, super-G 23.8 ± 2.7 m/s, giant slalom 17.7 ± 2.3 m/s (8,9)). FIS mandates that competitors wear a helmet that is certified under international standards for recreational skiing (ASTM 2040 and EN 1077). For the EN 1077 test procedure, a rigid ISO headform is inserted into the helmet and dropped from a height of 1.5 m, corresponding to 5.4 m/s, onto a flat fixed anvil. In order to pass the test, on impact, peak acceleration imparted to the headform cannot exceed 250 g (gravitational acceleration). Helmets used in downhill, super-G and giant slalom have to pass an additional drop test at a speed of 6.8 m/s, corresponding to a drop height of 2.4 m (13)." Theoretically, FIS's high energy helmet impact test should extend the protective function of helmets to a range of more severe impacts consistent with the sport. Ideally, the effects of this change will be evaluated epidemiologically and biomechanically. An important aim of a biomechanical evaluation is to establish the distribution of head impacts in ski crashes by location and severity (impact speed, conditions and injury outcome, etc.) (5,26).

Paragraph Number 5 Helmet standards are performance based. The helmet is subjected to a series of defined tests and the performance under those conditions is assessed against safety criteria. One of the most important characteristics of the helmet is its ability to attenuate impact energy and thereby reduce the forces applied to the head and the head's acceleration. In impact energy attenuation tests a helmeted headform is dropped from a specific height and the headform's linear acceleration is measured. It is imperative that the severity of the impact, e.g. the velocity, reflects a range of factors including the risk management objectives for the sport and the distribution of head impact velocities in the sport. Regarding the former, a sport may decide to focus on reducing the more severe spectrum of head injuries, only concussion or take a balanced approach to the range of injury risks. One method that has been applied extensively in other fields of crash protection to inform performance standards is crash reconstruction. The authors and others have demonstrated that crash reconstruction concepts can be applied to sport, e.g. knee injury and concussion, and have developed video based methods for estimating the kinematic characteristics of injury situations (15,16,17,20). To date, little is known about the distribution of head impact velocities in competitive alpine skiing.

Paragraph Number 6 The aims of this case study were to: estimate head impact velocities in a crash at a World Cup downhill skiing event that resulted in the athlete suffering a severe TBI, using a Model-Based Image Matching (MBIM) technique (16,17) and, demonstrate the utility of this method for future implementation in a cohort study of ski crash incidents.

Case Report

Paragraph Number 7 Description of crash: A 30-year old male World Cup alpine skier crashed during official downhill training in Kitzbuhel in January 2011. The athlete provided informed consent for this case to be analyzed and for his medical details to be made available. And this study was approved by the Ethics Committee "Regional Committee for Medical and Health Research Ethics – South East". At takeoff from the "Mausefalle" jump, the skier was observed to rotate about his longitudinal axis. As a result of this rotation, when he landed his skis had an angle relative to the body's downhill velocity vector. The skier lost control at touch down, fell laterally and struck his head. (Fig 1) He immediately became unconscious.

Paragraph Number 8 Injury: He suffered a subdural hemorrhage and was kept in an artificial coma for 10 days following surgery. The athlete recovered fully, but subsequently retired from skiing because of the injury.

Paragraph Number 9 Environmental conditions: The temperature at the race start was -7° C and the density of the snow surface was estimated to be 300 – 550 kg/m^3 (5). Video reconstruction method: Video from four camera views was obtained in full high definition (HD) format (1920×1080i, 25 Hz). Video was converted to uncompressed TIFF files using Adobe Premiere Pro and de-interlaced using Adobe Photoshop to obtain an effective frame rate of 50 Hz. The video sequences were time aligned manually using key events, such as ski or head impacts.

Paragraph Number 10 During the World Cup event, one of the co-authors (MG) collected highly accurate coordinates of the terrain surface, 27 distinct landmarks on the slope and surroundings and 2 camera positions (Fig 2A) using a differential global navigation satellite system (Alpha-G3T, Javad, USA). The captured terrain surface points allowed the reconstruction of a detailed and accurate 3D model of the slope (10,11) (Fig 2B). The 27 landmarks and camera positions were used for the spatial calibration of the video perspectives.

Paragraph Number 11 The three-dimensional kinematics of the skier, were estimated using a MBIM technique. Matching was performed using the commercially available program Poser 4 (Curious Labs Inc., Santa Cruz, California, USA). The slope and a skeleton model (Zygote Media Group Inc, Provo Utah, USA) were matched to the background video for each frame (Fig 3). The model consisted of five rigid segments (pelvis, abdomen, chest, neck and head) in a hierarchical structure with the pelvis as the parent segment. The pelvis has six degrees of freedom model (rotation and translation) whereas the motion of the other four segments was described with three rotational degrees of freedom relative to their parent, for example the head relative to the cervical spine.

Results

Paragraph Number 12 Immediately before head impact, the downward velocity component (normal to the slope surface) was estimated to be 8 m/s. Immediately after impact, the upwards velocity (normal to the snow surface) was 3m/s (Fig 4). During the impact, the velocity along the slope surface was reduced from 33 m/s to 22 m/s. Key events in the crash are presented in Fig 4. The slope angle at impact was estimated to be 34° and the impact angle was estimated to be 14° relative to the surface.

Paragraph Number 13 The head experienced a large increase angular velocity in the head's frontal plane to approximately -80 rad/s (head lateral flexion to left) as a result of the ski and pelvic ground impacts (Fig 5). This was followed by a large change in frontal plane head angular velocity (100 rad/s) during the head impact to approximately 20 rad/s (head lateral flexion right).

Discussion

Paragraph Number 14 Knowledge on optimal helmet performance criteria for World Cup alpine skiing is limited, in particular representative helmet impact severities. In the current study, the head change in velocity was estimated to be 11 m/s both along the slope and normal to the slope. Associated with this velocity change was a substantial transfer of energy to the head which was considered to be leading cause of the severe brain injury. The head impact velocity in this case is comparable to a motorcycle crash at highway speed (3).

Paragraph Number 15 The results of this case study reinforce the direction taken by FIS with regards to helmet performance requirements, i.e. the addition of a 6.8 m/s – high energy – helmet impact test. Although this single case study suggests that real world head impacts may be more severe than FIS's requirement, further research is required to determine the distribution of head impact velocities. There are other factors that require consideration when real world impact speeds are translated into laboratory helmet tests: the impact anvil is typically rigid, which will produce a higher head acceleration compared to an impact in the real world against a compliant surface such as snow/ice; and, the headforms used in laboratory tests are typically rigid and will also result in a higher head acceleration compared to a human head or equivalent headform (18). Therefore, laboratory helmet impact tests are often slightly less severe than real world impacts. In addition to the previous factors, the snow properties and impact angle in the skiing slope must be taken into consideration and assessed in a future study. Similar studies are required to understand the impact characteristics in other snow sports and alpine disciplines, e.g. snowboard half pipe and slalom, in order to optimize helmets for those athletes (19).

Paragraph Number 16 There are a few limitations in this study. The first limitation is that it is difficult to match all points perfectly at each camera view. Based on an analysis of the velocity components in a global frame assuming constant velocity (horizontal axes) or linear increase in velocity (vertical axis) during the flight, we estimated the average error to be within 1.5 m/s during the flight.

Paragraph Number17 We chose not to filter the rotational velocity as it was considered that this would give the most realistic estimate of the peak angular velocity. An error in the rotational matching of the head could contribute equally to an under- or over-estimation of the velocity. The estimated angular velocity is under-estimated most likely due to the limited frame rate.

Paragraph Number 18 The reconstruction method provides valuable estimates of head impact velocities that can inform the development of helmet performance criteria and standards. However to be most effective, this method needs to be embedded in a structured research program, such as a cohort or case-control study, of crash events that lead to injury outcomes throughout the full spectrum of no injury to the most severe injury. Such a research program will provide the distribution of head impacts by velocity, contributing factors (e.g. snow surface and helmet and injury). If, hypothetically, such a research program identified a tight distribution of head impacts similar to this case study, this would provide the evidence base to increase the impact speed in a helmet test. Further refinement and focus on issues related to angular head acceleration, may provide justification for the introduction of relevant oblique impact tests (19). In addition, future consideration should be given to instrumenting helmets in competitive alpine skiing, as has been done in other sports (19). This may assist in studying injury risk and helmet performance requirements, but could also be valuable for the clinical management of the injured skier.

Paragraph Number 19 To summarise, this method requires the measurement of the spatial coordinates of the competition slopes, environmental conditions and multiple video views of crash events.

Paragraph Number 20

In conclusion, a unique combination of HD video footage and accurate measurements of landmarks in the slope enabled a detailed analysis of head impact velocity in this case of severe/critical TBI. The estimates can provide crucial information on how to prevent TBI through helmet standards and design criteria

Conflict of interest statement

There is no conflict of interest statement.

Ackowledgements

The Oslo Sports Trauma Research Center has been established at the Norwegian School of Sport Sciences through generous grants from the Royal Norwegian Ministry of Culture, the South-Eastern Norway Regional Health Authority, the International Olympic Committee, the Norwegian Olympic Committee & Confederation of Sport, and Norsk Tipping AS. This results of the present study do not constitute endorsement by

ACSM.

Figure legends

Figure 1: Key crash events. A) Flight phase 1, 1000 ms before head impact. B) Flight phase 2, 600 ms before head impact. C) Initial ski contact 200 ms before head impact. D) 100 ms before head impact. E) Head impact. F) 275 ms after head impact

Figure 2: A) Examples of landmarks measured. B) The resulting 3D terrain model with gates and calibration landmarks in color.

Figure 3 : MBIM analysis screenshot at the point of head impact. We calculated the velocity of the head center point (as defined in the Zygote skeletal model) using a cubic spline function (Woltring,1986) with a 7 Hz cut-off. The head linear velocity was expressed relative to a coordinate system aligned to the surface of the landing area. The head rotation signal was not filtered. The head rotational velocity was expressed about the axes of the local head coordinate system.

Figure 4: Head translational velocity (m/s), relative to the slope surface. The dotted vertical line indicates the initial ski contact with the ground. The solid vertical line indicates head impact.

Figure 5: Head rotational velocity (rad/s), relative to the slope surface. The dotted vertical line indicates the point of initial contact of the ski to the ground. The solid vertical line indicates the point of head impact.

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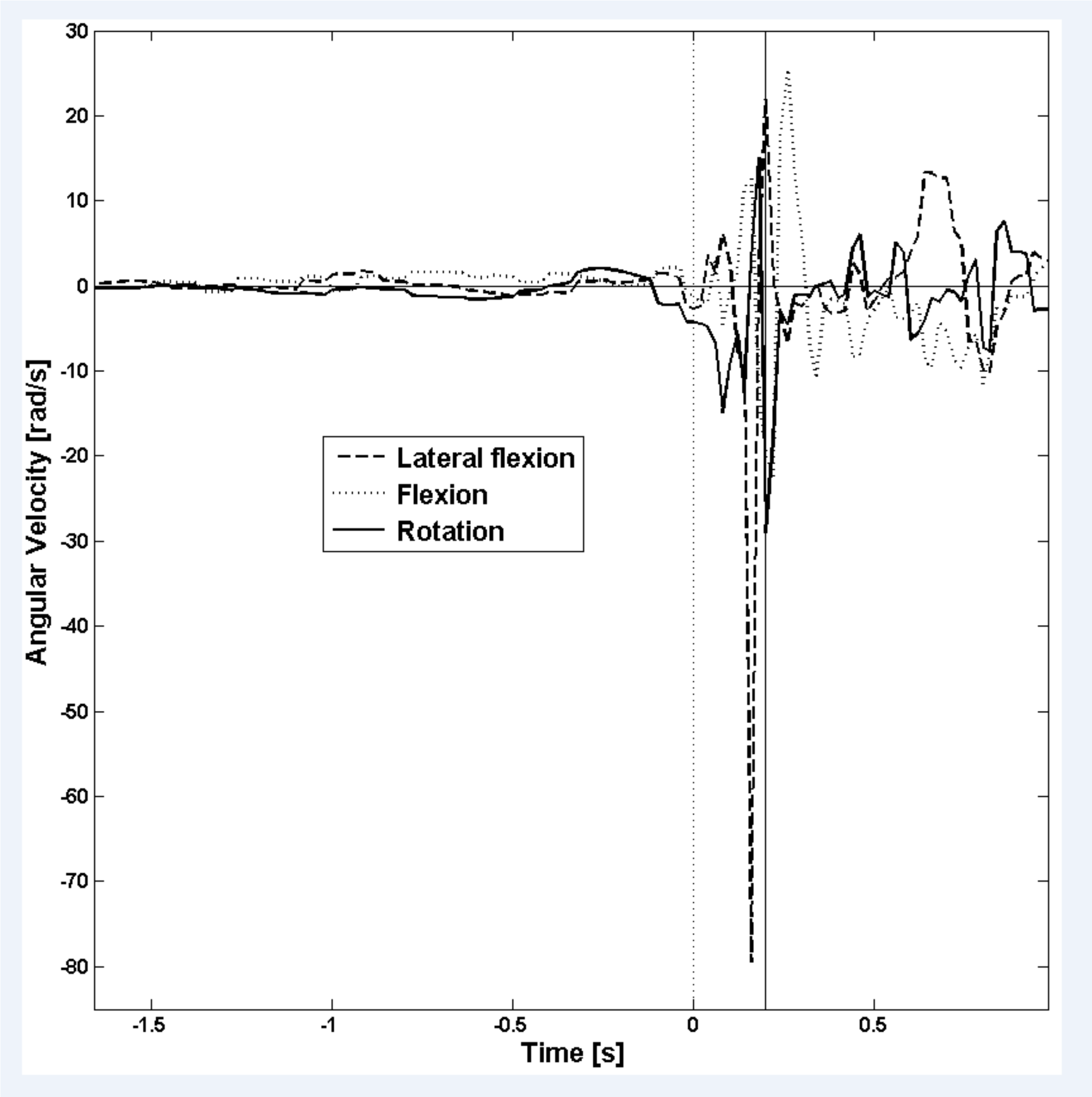
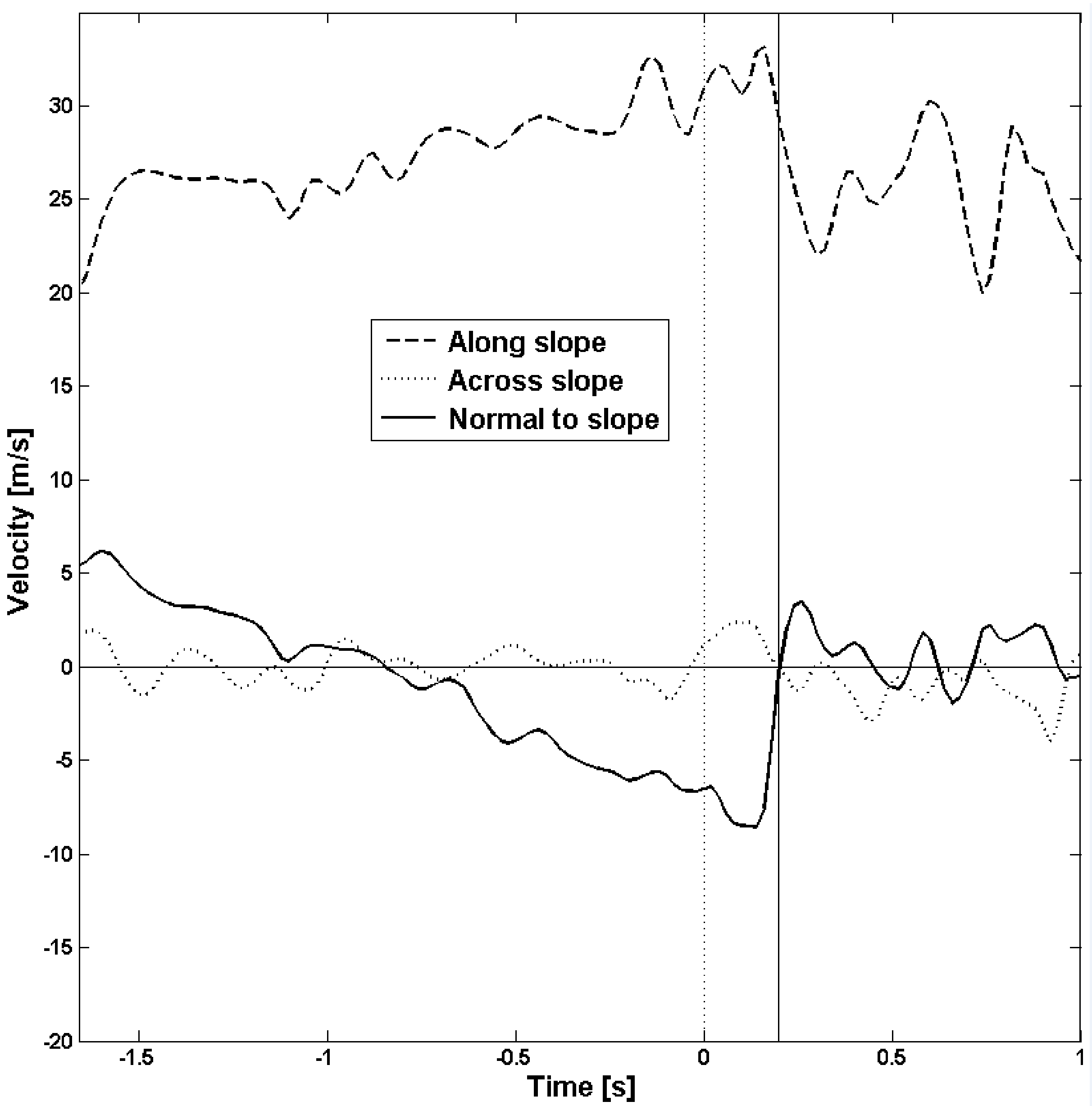

30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Angular Velocity [rad/s]
Lateral flexion
Flexion
Rotation
-1.5
-1
-0.5
0
0.5
Time [s]



Along slope
Across slope
Normal to slope
Velocity [m/s]
Time [s]
30
25
20
15
10
5
0
-5
-10
-15
-20
-1.5
-1
-0.5
0
0.5
1