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A biomechanical analysis of how rider behavior and equivalent fall height affect landing stability in World Cup Slopestyle for freeski and snowboard

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Abstract

Purpose: The purpose of this project was to investigate different rider behavioral factors along with Equivalent Fall Height (EFH), to see how they affected landing stability for World Cup Slopestyle athletes on freeski and snowboard. Landing stability was used as a surrogate measure of injury risk.

Methods: The data was collected from a Slopestyle competition in Seiser Alm, using a geodetic video method. 3-dimensional models of the athletes' center of mass trajectories were reconstructed, so physical parameters such as EFH could be calculated. Further, a qualitative assessment of landing stability and rider behavioral factors was done, including average angular velocity (ω_{avg}), axial motions, and rider orientation during landing. Landing stability was classified as "good" or "bad", and logistic regression with landing stability as the dependent variable were used to calculate probability of bad landing stability with different values of EFH and rider behavioral factors.

Results: Snowboarders showed bad landing stability twice as often as skiers, which can be explained by elementary differences in attachment to equipment and range of motion. EFH significantly increased probabilities of bad landing stability for skiers and snowboarders, while ω_{avg} significantly increased probabilities of bad landing stability for snowboarders. Skiers showed an interaction effect between ω_{avg} and axial motions, where monoaxial maneuvers showed higher probabilities of bad landing stability compared to multiaxial maneuvers on high ω_{avg}. This can be caused by a higher proportion of the ω_{avg} around one axis, and not distributed around several axes. Switch landings significantly increased the probability of bad landing stability for snowboarders, but not for skiers.

Conclusion: For skiers, increased EFH values, along with high ω_{avg} in monoaxial maneuvers showed the highest probabilities of bad landing stability. For snowboarders, increased EFH values, together with increased ω_{avg} and switch landings gave the highest probabilities of bad landing stability. This means that rider behavior impacts landing stability, which emphasizes that keeping EFH values low is important.

Table of Contents

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1. Introduction

In this project, Slopestyle athletes are being observed and analyzed in their natural competitive habituate. Physical variables and rider behavioral factors of several runs have been investigated, with an aim to map out how different factors impact landing stability which is defined as a surrogate measure of injury risks, for male and female athletes on freeski and snowboard. The investigation of this thesis is a part of a bigger project that was initiated by IOC and FIS in 2017 and spans over several years. Different scientists and students have participated in data collection, processing, and analyses. For this thesis, the methodology for the collection and processing of data will only be briefly described, since it happened 3 years before the current master thesis took place. The focus will be on the data analyses, and the assessment of rider behavior.

This thesis is written as an article with an extended theory part. For methods, see the article. The appendices provide explanation of variables included in the observational assessment of rider behavior (appendix 1), and probabilities for an unstable landing outcome with different states and values of independent variables included in the logistic regression (Appendix 2). List of figures and tables are presented at the end.

2. Definition of terms

Airtime:	**The time the athlete is airborne from takeoff to landing.**
Approach:	The part of the hill when the athlete develop velocity.
Bucket:	The flat, more horizontal part after the landing area.
Deck:	The horizontal/flat part of the jump between the kicker and the landing area. Desirably not in contact with the athlete.
Goofy stance:	When the right foot is the dominant front foot of a snowboarder.
Kicker:	The total construction of the ramp of the jump.
Knuckle:	The change of incline from the deck to the landing area.
Monoaxial:	A maneuver that has rotation in one axis.
Multiaxial:	A maneuver that has rotation in several axes.
Pop:	Muscular work on the lip of the takeoff to alter the velocity vector.
Regular stance:	When the right foot is the dominant front foot of a snowboarder.
Rider behavior:	Describes the maneuvers and choices of the athlete during a jump. Defines complexity of jumps.
Sweet spot:	The ideal landing point for smallest impact values.
Switch orientation:	When the skiers are orientated in the opposite direction of the velocity vector, or the snowboarders are riding with their dominant front foot in the back.
Takeoff:	The above surface of the kicker, that sends the athletes airborne.

3. Theory

3.1 Big Air and Slopestyle sports

The two snow sport disciplines Big Air and Slopestyle have one course element that is common for them, and that is jumps. This thesis will assess different aspects of jumping in Slopestyle, that might also apply for Big Air competitions.

3.1.1 Slopestyle

Slopestyle is a discipline within snowboard and freeski where the athlete performs maneuvers on a slope with different sections that each contains park features such as quarter-pipes, rails, boxes, and jumps. Competitions are divided into qualification heats, semifinals, and finals. Qualification heats holds 12-30 participants, while the finals consist of 10-12 male competitors or 6-12 female competitors (Fédération Internationale de Ski, 2020, pp. 84-86). According to ICR, the best of two runs count in qualification and semifinals. This applies to finals as well, only here it may be the best of two or three runs, depending on the competition (Fédération Internationale de Ski, 2022, p. 23).

3.1.2 Big Air

Big Air is a discipline within freeski and snowboard that consists of one big jump where athletes carry out extraordinary maneuvers. Big Air competitions are divided into qualification heats, semifinals, and finals. In accordance to standard competition formats from the International Ski Federation (FIS) a qualification heat usually consists of 12-30 participants, while the final holds 10-12 male competitors, or 6-12 female competitors (Fédération Internationale de Ski, 2020, pp. 84-86). Following the International Competition Rules (ICR), the athletes get points based on the best score of two runs in the qualification heat, and best two scores of three runs in the semifinal and finals (Fédération Internationale de Ski, 2022, p. 23).

3.1.3 Course design in Slopestyle and Big Air

Guidelines from FIS (Fédération Internationale de Ski, 2018, pp. 76-77) states that the different sections of a Slopestyle course may contain several features on the same location, creating different lines the athletes can choose between. The minimum width of the course should be 30 meters. Olympic courses should have at least three jumps in a row, and the athletes must hit minimum six features. The run should last at least 20 seconds, and for elite athletes the vertical drop from the start to the end of the course should be minimum 150 meters, with an average incline of at least 12 degrees. The course should induce a technical challenging run that both male and female athletes can perform (Fédération Internationale de Ski, 2020, p. 71).

According to FIS (Fédération Internationale de Ski, 2020, p. 71), the inrun of a Big Air jump should be at least 30 meters, with an angle of minimum 20 degrees. The height of the kicker should be over two meters. The jump should be five meters wide with a takeoff angle at minimum 25 degrees. For elite athletes, the length from takeoff to landing should be minimum 15 meters. The landing area should be at least 20 meters long and 20 meters wide, with an angle that corresponds to the takeoff angle with a minimum value of 28 degrees.

3.1.4 Judging criteria in Slopestyle and Big Air

In snowboard and freeski, the athletes get judged based on five different criteria that all are equally considered: variety, difficulty, execution, amplitude, and progression. Moreover, the judges look at the overall flow of the run, including the sequence of maneuvers, the use of the course and the level of risk in the athletes maneuvers (Fédération Internationale de Ski, 2019, p. 10). Variety will prove the athletes' abilities to perform different maneuvers in a routine, which particularly applies to Slopestyle. The athletes also show variety when a sequence of maneuvers differ in variables such as body orientation during takeoff or landing, direction of rotations and the use of multiple axes etc. (Fédération Internationale de Ski, 2019, pp. 15-16). Difficulty will describe the complexity of the maneuvers, which includes the number and directions of rotations, the height of the jump, the risk taken and what types of grabs that are performed (Fédération Internationale de Ski, 2019, p. 13). When evaluating execution, the judges consider among other things, the use of the course and the timing of the maneuvers from takeoff to landing (Fédération Internationale de Ski, 2019, p. 11). Amplitude represents the height of the jump. By jumping higher, airtime increases which enhances the athletes' possibility of better execution of the maneuvers (Fédération Internationale de Ski, 2019, p. 15). At last, the progression criteria is based on new or uncommon maneuvers and creativity of the athletes (Fédération Internationale de Ski, 2019, p. 16). Mistakes and falls are considered when giving a score. The judges' earlier experiences, the course inspection and personal preferences will add a subjective layer to the overall score (Fédération Internationale de Ski, 2019, p. 10).

3.1.5 Difference between male and female athletes

In Slopestyle and Big Air, male and female athletes compete on the same courses to keep event formats efficient, time- and cost-wise. Therefore, jumps and park features should be designed to be appropriate for both sexes. Hence, only skill level and competition format differ between sexes in competitions, not external factors. Competition formats depends on the number of participants of each sex (Fédération Internationale de Ski, 2020, p. 88).

3.2 *Epidemiology*

Through the international Olympic committee's (IOC) long-term work on the prevention of injuries, it was revealed that Big Air and Slopestyle often show one of the higher rates of injury among the Olympic winter sports (Palmer et al., 2021, p. 2; Ruedl et al., 2012, p. 2; Soligard et al., 2019, p. 3; Soligard et al., 2015, p. 2; Steffen et al., 2017, p. 2). These disciplines are characterized by high-speed and big jumps. More advanced maneuvers demand more airtime which can be obtained by bigger jumps. This results in the athlete being exposed to greater forces upon landing, and thus bigger impact on the athletes' bodies (Moore & Hubbard, 2018, p. 811; Swedberg & Hubbard, 2012, p. 122). Big jumps may therefore induce higher injury risks. Several studies have pointed out jumps and falling from heights as sources to injury (Carús & Escorihuela, 2016a, p. 417; 2016b, p. 87; Moffat et al., 2009, p. 260; Russell et al., 2013, p. 172; Russell et al., 2014, p. 3). In the following sections, differences in pattern and severity of injuries, related to sex, equipment and skill level will briefly be explained.

3.2.1 Freeski versus Snowboard

There have been several groups investigating injury patterns of recreational snowboarding and freeskiing in terrain parks (Carús & Escorihuela, 2016a, 2016b; Russell et al., 2013), and studies have shown that injury rate and injury severity increases when attending terrain parks compared to regular slopes, particularly for skiers (Goulet et al., 2007, p. 403). Carús and Escorihuela (2016a, p. 417) saw that skiers in a terrain park had an injury incidence of 0,9 per 1000 skier runs, and an injury incidence as high as 2,9 per 1000 run for big jumps (Carús & Escorihuela, 2016b, p.

88). They saw that jumps not only accounted for the most injuries, but also for the more severe ones (Carús & Escorihuela, 2016b, p. 87). Russell et al. (2013, p. 174) did a similar investigation on snowboarders in a terrain park, and found an incidence rate of 0,75 per 1000 runs. Also here, jumps together with half pipe accounted for the highest injury rate with 2,56 per 1000 run (Russell et al., 2013, p. 174).

For recreational skiers and snowboarders, studies have shown that the most common injured body parts due to aerial features including jumps, were the head, wrist, and shoulders (Carús & Escorihuela, 2016a, p. 417; Russell et al., 2013, p. 175). Goulet et al. (2007, p. 403) saw that snowboarders were more likely to injure the upper extremity compared to skiers, that more often got lower extremity injuries (Goulet et al., 2007, p. 404), but other studies have seen that injuries to the upper extremity are more frequent for both skiers and snowboarders in terrain parks (Carús & Escorihuela, 2016a, p. 417; Moffat et al., 2009, p. 260; Russell et al., 2013, p. 175). Moreover, trunk injuries have shown to be more common in terrain parks compared to regular slopes for both skiers and snowboarders, as well as injuries to the head and neck were more common for skiers only (Goulet et al., 2007, p. 403). Steenstrup et al. (2014) did a cohort study to examine the incidence of head and face injuries in freestyle skiers, snowboarders, and alpine skiers. Of 2080 injuries, 11,8 % were to the head and face. The incidence was bigger in freestyle skiers and snowboarders with 5,7 and 5,0 injuries per 100 athletes respectively, than in alpine skiers with a rate of 3,5 injuries per 100 athletes (Steenstrup et al., 2014, p. 2). Almost 25 % of the injuries to the head and face were severe, causing time loss from training and competition (Steenstrup et al., 2014, p. 4). Torjussen and Bahr (2005, p. 375) also saw that snowboard disciplines in total had an injury rate of 38% and 36% for back and chest injuries, mostly happening in disciplines that includes jumps, such as Big Air. This shows how the sports brings risks of severe spine injury.

Among the types of injuries that often occurs, fractures seem to be a common injury type for both skiers and snowboarders (Carús & Escorihuela, 2016a, p. 417; Russell et al., 2013, p. 174; Russell et al., 2014, p. 3; Tarazi et al., 1999, p. 179). According to Carús and Escorihuela (2016a, p. 418) fractures occurred more often with aerial features than with non-aerials. They discuss that the higher occurrence of fractures may be a result of the force absorbed upon landing after being airborne (Carús & Escorihuela, 2016a, p. 418).

3.2.2 Male versus female athletes

When investigating whether injury pattern in Big Air and Slopestyle differ between sex, different outcomes have been observed. In the Youth Olympic winter games in Lausanne 2020, the injury risk was bigger for female compared to male athletes (Palmer et al., 2021, p. 3). This also accounted for Slopestyle skiing in the Olympics in Sochi 2014 (Soligard et al., 2015, p. 2). Furthermore, when investigating head injuries among snowboarders and freestylers through seven seasons of FIS World Cup, Steenstrup et al. (2014, pp. 2-3) found that female athletes showed a higher incidence of head injuries compared to male athletes. However, Torjussen and Bahr (2005, p. 375) didn't find any difference in injury incidence between male and female athletes when investigating injuries in national elite snowboarders, and Palmer et al. (2021, p. 2) did not find any differences between male and female athletes in the severity of the injuries.

Also in terrain parks scientists have conflicting findings. Russell et al. (2014, p. 3) saw that female athletes above 12 years showed a higher injury rate, and a higher rate of severe injuries compared to male athletes, while Carús and Escorihuela (2016b, p. 87), saw a tendency of a higher injury risk among male compared to female athletes. Injury characteristics have also shown to differ between sexes. Rugg et al. (2021, p. 3) showed that male athletes frequently injured their shoulder and chest, while female athletes had a higher injury rate for the back and pelvis. For both male and female athletes, injuries to the head were the most prevalent. Fractures, dislocations, and wounds have been reported more prevalent for male athletes, while sprains, strains and contusions were more frequent for female athletes (Rugg et al., 2021, p. 3).

Studies from terrain parks cannot be fully generalized to sex differences in Big Air and Slopestyle competitions, because it is data from recreational and not elite athletes, and jump dimensions are unknown for these studies. However, it may reflect differences in mindset between male and female athletes. Studies have seen that male athletes scores higher in investigations around thrill and sensation seeking (Breivik et al., 2017, p. 268; Cross et al., 2013, p. 2). According to Breivik et al. (2017, p. 271), sensation seeking seem to correlate with risk taking. Looking at it from a Big Air and Slopestyle perspective, it can mean that male athletes take bigger risks. This theory is supported by Rugg et al. (2021, p. 3) finding that male athletes more often got injured on more advanced slopes compared to female athletes, and that severe and fatal injuries were more common among male snowboarders (Rugg et al., 2021, p. 3).

3.2.3 Expert versus novice level

It seems that upper extremity injuries are normal among recreational athletes. However, studies show that injuries related to the knees are more common among elite athletes, and that wrist injuries occurs, but more rarely compared to recreational athletes (Major et al., 2014, p. 4; Steffen et al., 2017, p. 2; Torjussen & Bahr, 2005, p. 375; 2006, p. 232). The bigger jumps typically used by elite athletes, however, expose the athlete to larger forces, especially upon landing (Hubbard et al., 2009, p. 178; Hubbard & Swedberg, 2012, p. 3; McNeil et al., 2012, p. 6), increasing the impact the athlete needs to resist. The same tendency can be seen for different skill levels in terrain parks. According to Goulet et al. (2007, p. 403), experts more often seem to be exposed to severe injuries compared to novices in terrain parks. They discuss how more experienced athletes may take more risks and ride with higher speed. Russell et al. (2014, p. 3) agrees to this finding, stating that beginners showed lower rate of injuries compared to intermediates.

On the other hand, this is contrary to the finding of Carús and Escorihuela (2016b, p. 88), that said the risk of severe injuries were higher among novices than experienced athletes. They explain it with the possibility that novices try maneuvers beyond their skill level, which may lead to injury because they do not manage to carry out the maneuvers with control. Other studies also report that novices show a higher injury incidence compared to more experienced athletes (Bladin et al., 1993, p. 702; Idzikowski et al., 2000, p. 827). Different findings in terrain park investigation might be due to definition of experience level, bias related to self-reported experience level or an underestimation of injury incidence if less severe injuries did not get reported.

3.3 Jump design and injury risk

Most jumps are shaped based on experience and practitioners' knowledge. It is often an idea, the snow quality, and the existing volume of snow that determines the final jump design and dimensions. This practice has limits, and the design might end up with jump dimensions that don't correspond with each other, causing regions with high landing impacts (Böhm & Senner, 2008, p. 170; McNeil & McNeil, 2009, p. 162). Because of this, several scientists have looked at jump dimensions and properties, to ensure safe rides for the athletes (Böhm & Senner, 2008; Hubbard et al., 2009; Hubbard & Swedberg, 2012; Levy et al., 2015; McNeil, 2012a, 2012b; McNeil et al., 2012; McNeil & McNeil, 2009; Moore & Hubbard, 2018; Petrone et al., 2017; Shealy et al., 2011; Swedberg & Hubbard, 2012; Wolfsperger et al., 2021b). These investigations consider how the different elements of the jump affect safety.

To ensure safe conditions for athletes in Big Air and Slopestyle, jump properties and measurements need to be carefully calculated and planned. There seems to exist a common understanding that the force athletes have to control in the takeoff, when generating rotation and adjustment of the COM trajectory, and the force athletes need to absorb in the landing can lead to unbalance. This might induce an injury risk because this unbalance may throw the athlete out of control (Hubbard et al., 2009, p. 178; Hubbard & Swedberg, 2012, p. 3; McNeil et al., 2012, p. 6; Swedberg & Hubbard, 2012, p. 122). Löfquist and Björklund (2020, p. 1567) showed that a skier is exposed to a force that correspond to the double of their body weight when landing a Big Air jump. The impact the athletes need to withstand from the ground is known as the ground reaction force (GRF). GRF varies with the weight and velocity of the athlete, and the curvature of the terrain (Vernillo et al., 2018, p. 3). According to McNeil et al. (2012, p. 4), the amount of force that affect the athlete in the takeoff should not exceed 2g. Forces above 2g might send the athlete airborne with an uncontrolled posture. Minetti (1998, p. 1789) saw that athletes can absorb impacts in their legs that corresponds to the impact that would occur if falling along the gravity vector onto a horizontal distance, from a height of maximum 1,5 meters. Hubbard et al. (2009, p. 179) further proposed that landing impacts should not exceed impacts that would correspond to landing on a horizontal surface from a height of 1 meter. United States Terrain Park Council (USTPC) now uses an EFH of 1,5 meters as a guideline for all jump landing surfaces. In this section, the overall construction of jumps will be explained further, as well as the forces that influence the takeoff velocity.

3.3.1 Components of a jump

A jump consists of different components (Figure I). Starting from the beginning of the run, the approach is where the athlete builds up velocity. The transition area ensures an even transition between the approach and the takeoff. This curved transfer must avoid to expose the athlete to a high radial acceleration that would cause unbalance (McNeil et al., 2012, p. 4). The curvature of the transition area and takeoff, together with the length of the approach will influence takeoff velocity (McNeil et al., 2012, p. 3). The takeoff is also where the athlete can adjust the flight trajectory by muscular work and generate the angular momentum for the rotations during the airborne phase (McNeil, 2012b, p. 5). The maneuver area above the deck is the region where the athletes are airborne and perform spectacular maneuvers. The knuckle is where the slope changes incline from the deck to the landing area. This change is important since the athlete should land in the steeper part of the hill (McNeil et al., 2012, p. 4), typically referred to as “the sweet spot”, where the landing impact is at its lowest (Kulturdepartementet, n.d.; McNeil et al., 2012, p. 7). Airtime is the time period where the athlete is in the air. Airtime or amplitude, is important since it is a direct criteria of performance (Fédération Internationale de Ski, 2019, p. 15), and because it enhances the athletes’ possibilities to perform advanced maneuvers and rotations. The positioning of takeoff and landing area will define the length of the deck. By designing the deck shorter, athletes will land further down on the landing area. That way, airtime will be improved. Research however, have seen that increased airtime due to shorter table lengths and steeper landing angles, increased the sum of impact energies during landing (Böhm & Senner, 2008, p. 170). Böhm and Senner (2008, p. 170) argues that the increased landing impacts were a result of that the athletes landed at the flat part after the landing area, the bucket, and not in the steep part of the hill.

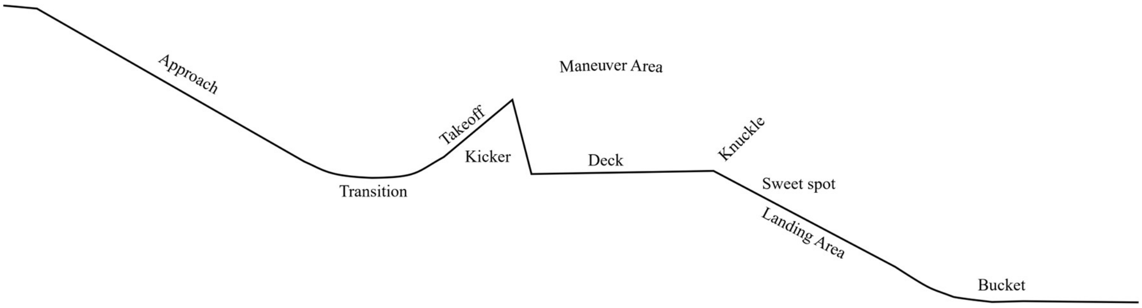

***Figure I**. A modified illustration from McNeil et al. (2012, p. 4), showing the geometry and components of a standard tabletop jump.*

3.3.2 Kicker designs

Bakken et al. (2011, p. 1317) saw that most of the observed injuries happened due to individual technical errors at the takeoff. The curvature of the takeoff needs to be well designed to keep the athletes' experience of radial forces as low as possible. As can be seen in Figure II, scientists have proposed several kicker designs, which differ in the distribution of compression forces. Uneven compression forces may reduce the athletes' control and balance. The dashed line in Figure II, shows a takeoff with a circular curvature. Here, the radius is constant throughout the whole takeoff, which leads to great compression forces in the beginning, because the velocity is high, and the curve is steep (Kulturdepartementet, n.d.). The dotted line is a coiled formed kicker with a gentle curvature and a rapid change of radius at the end. This type of design usually induces high forces at the end of the curvature (Kulturdepartementet, n.d.). The green line shows an elliptic curvature, where the dimensions and positioning of kicker height and length will be defined by the angle of the takeoff lip. For this shape, the radius of the curvature decreases along with the reduction of velocity throughout the takeoff. This might provide the athlete with an even compression throughout the curvature and enhances the ability to handle the radial acceleration in the transition from the inrun to the takeoff.

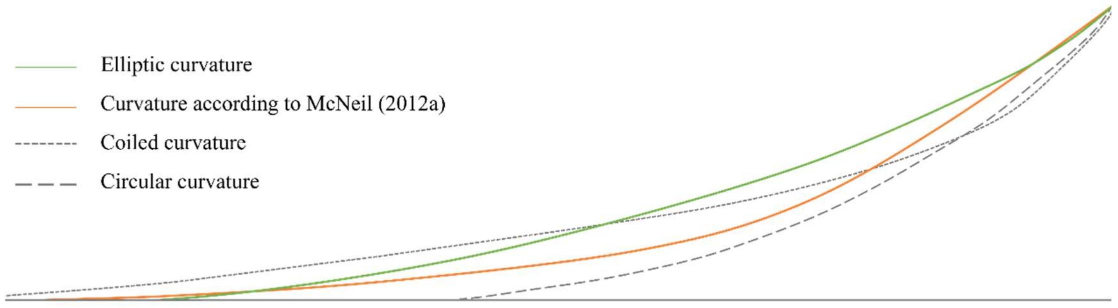

Figure II. *Modified illustration from Kulturdepartementet (n.d.) of four different takeoff curvatures. The green line shows an elliptic curvature where the radius decreases with the decrease of velocity. The orange line represents a curvature proposed my McNeil (2012a, p. 5) to avoid an involuntary inverted position in the air. The grey dotted line shows a rapid change to a smaller radius towards the end, while the grey dashed line has a constant radius all the way to the lip.*

Another aspect to consider when designing kickers, is how the takeoff affects the athlete's angular momentum during the airborne phase. According to McNeil (2012a, p. 6), many severe injuries involve landing on the head, neck or back. It is common for both snowboarders and skiers to be inverted in aerial maneuvers. One may be inverted because the athlete intentionally chooses a maneuver that requires rotation around a horizontal or sagittal axis. However, a concave curvature at the lip of the takeoff may send the athlete airborne with an unintentional rotation backwards (McNeil, 2012a, p. 1). To avoid this, McNeil (2012a, p. 5) proposes that the first part of the kicker has a constant radius in the beginning, while the last part is a linear part that covers a distance equal to 0,3 seconds times the athlete's takeoff speed, which is the time and distance it takes to regain balance after changing from a curved to a linear surface (McNeil, 2012a, p. 5). That type of curvature is shown as the orange line in Figure II, and is a guideline for all jumps in America (McNeil, 2012a, p. 6).

3.3.3 Deck length and landing area designs

In a standard jump, landing in the "sweet spot", is ideal in relation to injury risk (McNeil et al., 2012, p. 7). By jumping too far, the athlete may land in the bucket, while jumping too short may result in landing on the deck or the knuckle. Both landing areas expose the athlete to large forces (Böhm & Senner, 2008, p. 170; McNeil & McNeil, 2009, p. 162). To reduce the impact the athlete needs to absorb during landing, the takeoff angle and velocity need to be such that the resulting angle of the flight trajectory at touchdown should match the angle of the landing surface as much as possible, to reduce the component of velocity vector of the athlete that acts perpendicular on the snow surface (Hubbard et al., 2009, p. 178; Hubbard & Swedberg, 2012, p. 3; McNeil, 2012b, p. 11; McNeil et al., 2012, p. 6). Because velocity and takeoff angle will affect the athletes' flight trajectory, it can be difficult to know how long the deck length of the jump must be in order for the athlete to land in the sweet spot (Böhm & Senner, 2008, p. 165). By knowing the topography of the hill, and the forces that affect velocity, one can calculate how to position takeoff and landing area, so the athlete can land in the sweet spot. Calculating the trajectory of the athlete is complex, however. When performing a jump, the different forces one has to consider is gravity, air drag, lift and equipment-snow friction (Hubbard et al., 2009, p. 176). Friction, air drag, and lift are dependent weather conditions, and hence velocity at takeoff might vary substantially depending on external factors for the same inrun geometry (Wolfsperger et al., 2021a, p. 8; 2021b, pp. 1084-1085), which can cause the athlete to jump too short or too far, despite that the components of the jump were designed in accordance with each other. Therefore, a jump should be designed so the deck is short enough for the minimum velocity, and with a landing area that covers the maximum velocity that can be obtained by the athlete.

3.3.4 Different jump designs

Jump design will also influence airtime and safety. Figure III illustrates four common jump designs. The solid grey line, and the orange dashed line represent a Table-top jump and a Step-down jump respectively (Kulturdepartementet, n.d.). Both have linear horizontal decks, which lay almost as high as the lip of the takeoff for the Table-top, and lower for the Step-down jump (Kulturdepartementet, n.d.). If jumping too short on these types of jumps, one can risk landing on the deck or the knuckle. Blue and purple dashed lines represent the Roll-over and Step-up jump, respectively. The decks of these designs have a parabolic shape that follows the trajectory of the athlete and an even transition to the landing area (Kulturdepartementet, n.d.). The rollover-jump has its deck almost on the same height as the lip of the takeoff, while the step-up plateau is higher (Kulturdepartementet, n.d.). They induce a low fall height and may be consider safer. If the athlete jumps short, the impact on the athlete during landing is lower compared to landing on the knuckle of a Table-top or Step-down jump (Kulturdepartementet, n.d.).

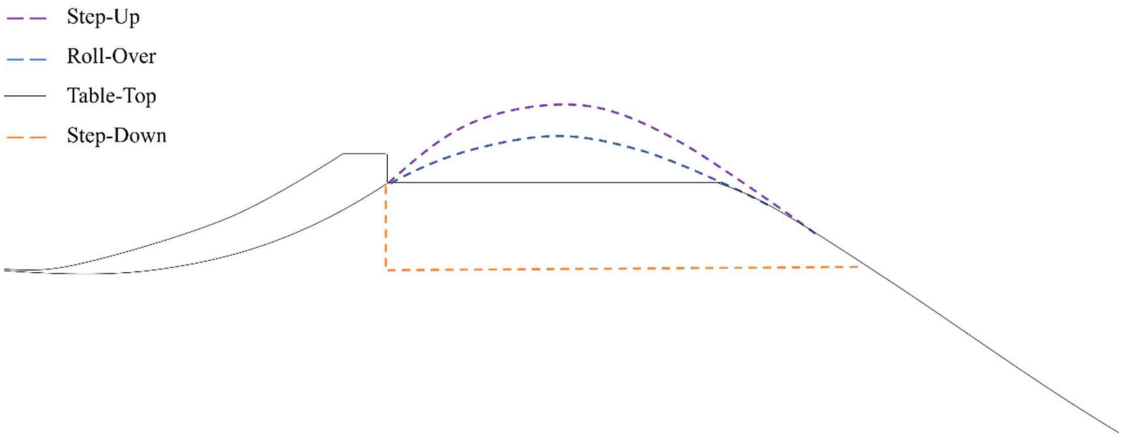

Figure III. *Four different jump designs are presented in this illustration inspired by Kulturdepartementet (n.d.). Purple and blue dashed lines represent the landing surface of a Step-Up jump and a Roll-Over jump, respectively, while the black solid line is the landing surface of a Table-top jump, and the orange dashed line is the landing surface of a Step-Down jump.*

The Table-top jump is the most common jump design (McNeil et al., 2012, p. 3), which might induce higher injury risk for the athletes compared to a Roll-over or a Step-up jump, but provides more airtime which enhances performance. The Step-down jump may induce higher injury risk because the deck lays at the same height as the beginning of the takeoff, narrowing down the preferred landing area. This leads to difficulties of deciding what speed is necessary to land safely (Kulturdepartementet, n.d.).

3.4 Surrogate measures of injury risk

The "sequence of prevention" is a four step model, that facilitates analysis and prevention of sport injuries (Kröll et al., 2017, p. 1644). Incidence and severity of the injury, followed by the injury mechanisms are mapped out as step 1 and step 2 respectively. Step 3 involves the introduction of a new prevention measure, before step 1 is being repeated as step 4, to see if the prevention measure show effect. The problem with this method is when dividing the group into smaller cohorts, such as male and female athletes on freeski and snowboard, the sample size gets too small. There is a chance that any potential effect will not turn out statistically significant, which results in a type 2 error (Kröll et al., 2017, p. 1644). To avoid a type 2 error, the effect size or the sample size needs to be bigger, which in many cases are unrealistic and unethical to achieve. Kröll et al. (2017, p. 1645) states that when dealing with small groups and specific injury types, the statistical power of the investigation will most likely be underpowered, and traditional statistical testing of hypotheses cannot be used. To compensate for the small sample size when testing the effectiveness of preventative measures, using surrogate measures have shown to increase statistical power (Kröll et al., 2017, p. 1645). By using surrogate measures, the sample size will not only consist of the actual injury that are being investigated, but also events that usually are related to the specific injury (Johnsson et al., 2018, p. 766). These events can be thought to represent a measure of the injury risk, and Kröll et al. (2017, p. 1645) concludes them to be valid as long as they are frequently related to the injury of interest.

Qualitative measures such as observation and video analysis have been frequently used to analyze the athlete's behavior and how it might affect performance and injury incidence (Bakken et al., 2011; Bere et al., 2014; Randjelovic et al., 2014; Steenstrup et al., 2018). According to Randjelovic et al. (2014, p. 5), athletes in ski-cross often lost control and balance before falling. This has also been reported for athletes in snowboard-cross (Bakken et al., 2011, p. 1317). Unbalance is therefore a potential surrogate measure of injury risk, since falling and landing from jumps have been related to injury incidence (Carús & Escorihuela, 2016a, p. 417; 2016b, p. 87; Moffat et al., 2009, p. 260; Russell et al., 2013, p. 172; Russell et al., 2014, p. 3). Landing unbalance may be caused by the impact the athlete is exposed to during landing, or related to rider behavioral factors, such as failing to stop or finish a rotation. Unbalance may also interrupt the “flow” of the athlete. This flow is established when an athlete and the context around, in this case the course construction, interacts in a balanced fashion and creates a unitized experience (Celsi et al., 1993, pp. 11-12). Ideally, a course design that provides the athlete with enough complexity to keep its exhilaration without losing control, creates a good flow. Interruption to this flow may result in lower confidence when approaching the next jump, which can reduce performance and increase injury risk (Hanton & Connaughton, 2002, p. 87). Because of this, observed landing stability can be used a surrogate measure and indicator of injury risk in Big Air and Slopestyle.

3.5 Injury risk factors

Injury risk factors is defined as factors that influence injury risk, and include rider behavior, Equivalent Fall Height (EFH), variables that affect velocity, and competition formats. Rider behavior describes the behavior of the athlete throughout the execution of the jump. EFH represents landing impact. Variables that affect the velocity of the athlete include external forces, topography of the slope and snow- and weather condition. Competition formats involve how different situations in competition triggers and the athlete to improve performance, but might also cause increased risk taking.

3.5.1 Rider Behavior

2.5.1.a “Pop”

Rider behavior have hardly been investigated, but can be thought to affect landing stability dependent on the choices of maneuvers or rotations. Rider behavior includes different variabilities that influences the ride, from takeoff to landing. The “pop” is a known rider variable (McNeil et al., 2012, p. 16). When athletes “pop”, they add muscular work on the lip of the takeoff and changes the velocity vector (McNeil, 2012b, p. 5). Athletes “pop” to increase airtime, which may enhance athletes’ performance, or to compensate for too much speed. Changing the velocity vector of the athlete, the jump trajectory at touchdown will change relative to the landing angle. This will in turn affect the EFH (Hubbard & Swedberg, 2012, p. 9). Because of this, the athlete’s “pop” is necessary to consider when calculating measures of a safe jump. According to McNeil (2012b, p. 12), “pop” speeds varies from -2.48 m/s to +1.12 m/s. Positive values refers to the actual “pop”, where the athlete increases the takeoff angle through muscular work, while negative values of “pop” occur when the athlete absorb and lower the takeoff angle to compensate for too much velocity in accordance to jump shorter. Hubbard and Swedberg (2012, p. 9) saw that differences in “pop” affected the EFH more than other conditional variables did, which means that variations in “pop” might be the most sensitive parameter to affect the EFH, and should be considered when designing a jump.

2.5.1.b Complexity of maneuvers

In addition to rider’s “pop”, other rider variabilities that can be interesting to look at, is for example how the athletes perform the different maneuvers. Complexity of maneuvers gives higher scores in competitions (Fédération Internationale de Ski, 2019, p. 13). Angular velocity and axial motions will affect the level of difficulty and complexity. Orientation of the athlete during takeoff and landing, as well as rotational direction in maneuvers are also variables that are interesting to look at. By challenging these aspects, performance can be improved, but injury risk may increase as well.

Angular velocity describes how fast the athlete rotates in a maneuver. A higher angular velocity might make the maneuver more complex because the athlete will have less time to orient oneself and adjust the velocity and position prior to a smooth and balanced landing. Also, generation of the angular velocity in the takeoff might be more demanding the higher the rotation rate that needs to be generated is. Furthermore, different maneuvers can be done around several axes. If the rotation only happens around for example a vertical axis, the athlete rotates in one plane, with his feet always below the body. If the maneuver happens around a horizontal axis, the athlete does a flip in a sagittal plane, either forward or backwards. Lastly, the maneuver may happen “off-axis”, or in several axes. Here the athlete both spin and flip, and the axes are less clear. Doing rotations around several axes may increase the level of difficulty, because the athlete needs to adjust the position and velocity in a more complex setting.

Other variables that vary are athlete orientation and direction of rotation. Athlete orientation explains which way the athlete is oriented on the takeoff and landing. Often, this is defined as normal or switch. For skiers, normal refers to when they are oriented facing towards the valley, and switch is when they are oriented towards the hill.

Technique of performing a maneuver might differ when skiers approach or land a jump normal or switch. Löfquist and Björklund (2020, p. 1567) did not find a difference when they investigated how landing normal or switch affected landing impact. They did however, observe a biomechanical difference, where the athlete showed greater flexion in the knees during normal orientation, with the upper body in a more upright posture (Löfquist & Björklund, 2020, p. 1569). Moreover, with switch orientation, perception is limited, and the athlete might have to adjust posture and COM to be able to perform the desirable maneuver or rotation.

For snowboarders, normal rider orientation refers to when they have their dominant front foot in front, while switch is if they have their dominant front foot in the back. If the snowboarder’s dominant front foot is the left foot, they are referred to as having a regular stance, while with a goofy stance, the right foot is their dominant front foot. Techniques might not differ between normal or switch orientation, but riding switch might be more complex assuming that the athletes have more control with their dominant front foot in front, which enhances their abilities to keep steady when there are perturbations to the snow surface. Due to differences in rider variabilities, complexity and difficulty of maneuvers change, which may affect landing stability.

Direction of rotation is a factor that mainly concerns snowboarders in this thesis. It refers to whether they rotate backside or frontside. If rotating frontside, they rotate on the heel edge of the board, with their front facing towards the valley. If rotating backside, they rotate on the toe edge of the board, and towards the hill. Backside and frontside rotations require different techniques, which therefore makes them interesting to investigate. Frontside rotation can be considered more advanced than backside rotation. A backside rotation will give a clear view over the landing area. In a frontside rotation, perception is limited because the athlete is facing away from the point of landing. Moreover, when rotating frontside, one spins towards the heel edge of the board, while preferred landing position might be on the toe edge to enhance any ability of controlling posture and balance when coping with landing impact and surface inconsistencies. It might be challenging to adjust posture before landing a frontside rotation, in order to land on the toe edge. For skiers, rotating left or right would not differ in technique, only in preference of the athlete, since rotating one direction might be more natural compared to the other. However, since rotation in both directions is important for performance, this preference or challenge might not exist for elite athletes.

3.5.2 Factors that affect inrun and flight mechanisms

The velocity and flight trajectory of an athlete is determined by several factors. There are forces that both accelerate and decelerate the athlete, as can be seen in Figure IV. Gravity is the force that accelerate the athlete down the hill, by pulling the athlete towards the center of earth (Sternheim & Kane, 1991, p. 65). In theory, heavier athletes can get a higher velocity than lighter ones if friction is held fixed. Air resistance depends on posture, apparel, and velocity (Wolfsperger et al., 2021b, p. 1084), and heavier athletes bring more kinetic energy due to increased mass. They will lose less speed through the transition and takeoff, and will potentially have a higher takeoff velocity. This might result in longer jumps for heavier athletes, which makes a short landing area challenging.

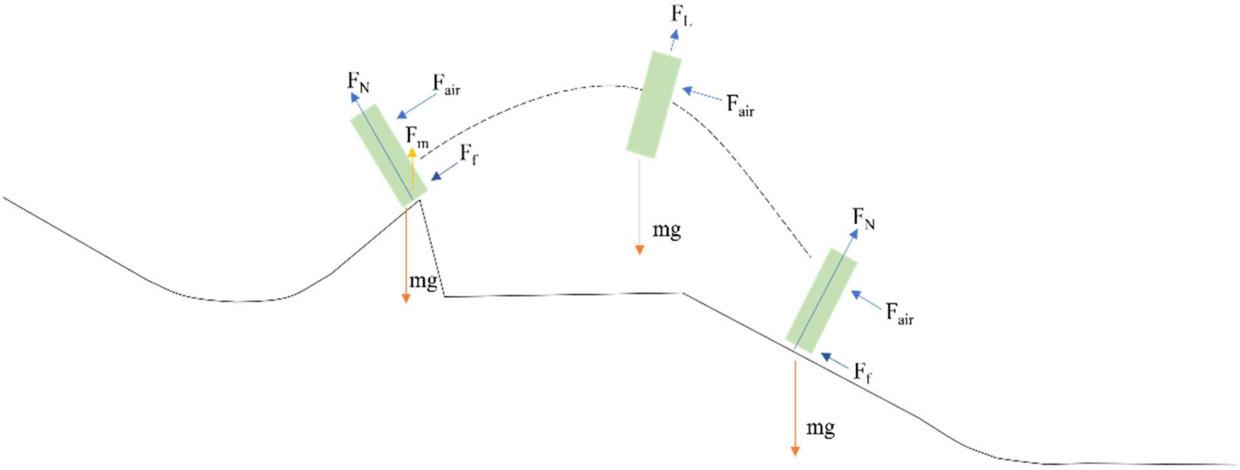

Figure IV. *The forces that affect the velocity and flight trajectory of the athlete during a jump in Big Air and Slopestyle. The green box represents the athlete during three points in a jump: one at the takeoff, one while being airborne, and one during landing. mg = gravity, Fm = muscle force during "pop", Fair = air resistance, Ff = friction, FN = ground reaction force and FL = lift. The dashed line represents the trajectory of the athlete. This illustration is not based on real scale between different components but is only a simple figure for representing forces.*

Friction and air resistance are the decelerating forces. Friction forces depends on equipment and snow conditions (Wolfsperger et al., 2021a, p. 8). Equipment may vary from athlete to athlete, and snow conditions from day to day. Air resistance have shown to vary with posture or change of apparel, especially with skiers (Wolfsperger et al., 2021b, p. 1084). By changing posture or apparel, one can manipulate the frontal area, and the athletes can compensate for slow or fast conditions (Wolfsperger et al., 2021b, p. 1085). The effect is not that big with snowboarders, which decreases their ability to compensate for limited velocity (Wolfsperger et al., 2021b, p. 1085).

3.5.3 Equivalent Fall Height (EFH)

An appropriate tool to quantify landing impact is EFH (Hubbard et al., 2009, p. 178; Hubbard & Swedberg, 2012, p. 3; McNeil et al., 2012, p. 6). Moore and Hubbard (2018, p. 811) defines EFH as "the kinetic energy associated with the landing velocity component perpendicular to the landing surface divided by mg, where m is the jumper mass and g is the acceleration of gravity". This means, that when falling along the gravity vector direction and landing on a horizontal surface, the amount of energy that needs to be absorbed in the landing is determined by the velocity the athlete has in the vertical direction just prior to the impact. This can be related to the height of the starting point of the fall, through the equation that convert potential energy to kinetic energy (Hubbard & Swedberg, 2012, p. 3; Swedberg & Hubbard, 2012, p. 122):

$$mgh = \tfrac{1}{2}mv^2$$

When landing on an angled slope, the impact is related to the component of the athlete's velocity that works perpendicular to the surface ($V_|$) (Hubbard et al., 2009, p. 178). The formula for Equivalent fall height will therefore be (Hubbard & Swedberg, 2012, p. 3):

$$EFH = \frac{v_|^2}{2g}$$

EFH can be used to measure the severity of landing impacts (Hubbard et al., 2009, p. 178; McNeil et al., 2012, p. 6). Shaping the jump to have a landing angle nearly equal to the athlete's trajectory at touchdown, minimizes the velocity component perpendicular to the snow surface, and thereby landing impact is reduced (Moore & Hubbard, 2018, p. 811). By limiting the impact during landings, one might avoid injuries. To the best of our knowledge, no studies have investigated the direct relationship between EFH and injuries, but several studies have calculated landing impact with different values of takeoff velocity and landing angles. However, knowledge on the topic is mainly based on results from computer simulations (Böhm & Senner, 2008; Hubbard et al., 2009; Hubbard & Swedberg, 2012; McNeil, 2012b; McNeil & McNeil, 2009; Swedberg & Hubbard, 2012). Only two studies have empirical data on impact during landing, measured with accelerometer (Hubbard et al., 2015; Petrone et al., 2017). This is the first study to relate EFH to landing stability.

The amount of energy that needs to be absorbed during landing increases with an increase of velocity (Swedberg & Hubbard, 2012, p. 122). Research suggests that a jump with a Table-top solution may not be the safest option when intending to reduce the EFH (Swedberg & Hubbard, 2012, p. 133). Figure V shows how the EFH throughout a Table-top jump is lowest at the sweet spot, approximately 15 meters through the jump (Moore et al., 2021, p. 6). In a standard Table-top jump, EFH increases linearly with an increase in horizontal length of the jump (Swedberg & Hubbard, 2012, p. 130). Consequently, a Table-top jump is sensitive to velocity and has a narrow landing area, which may result in athletes landing in areas with high values of EFH if not having the desired velocity.

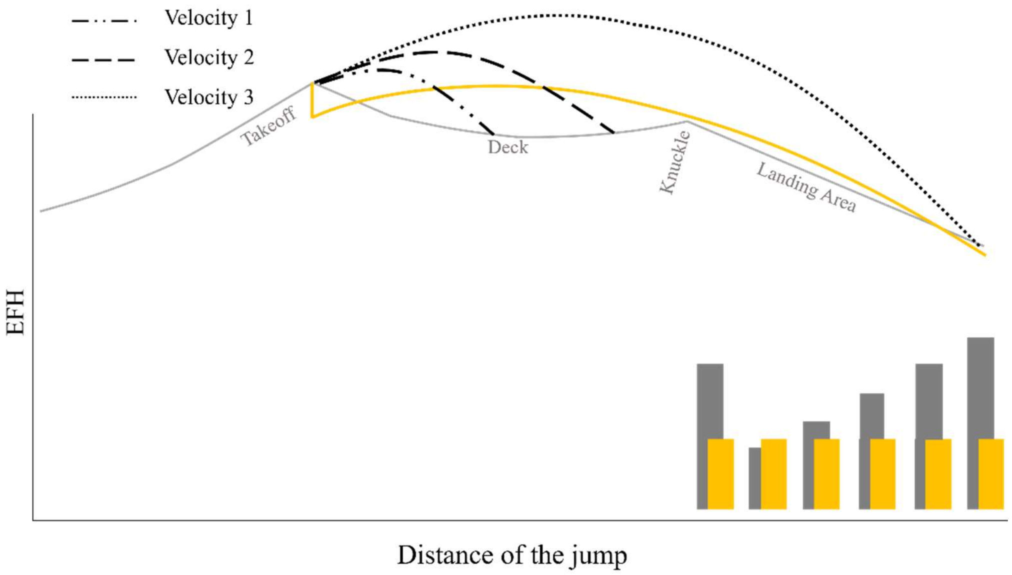

Figure V. *This illustration, inspired by Moore et al. (2021, p. 6) show how EFH changes (grey bars) with different landing points on a linear landing surface (grey solid line), and how EFH is kept constant (yellow bars) with a parabolic landing area (yellow solid line). The dashed and dotted lines represent flight trajectories with different velocities.*

A solution to maintain low EFH values is a more parabolic landing area (Hubbard et al., 2009, p. 180; Hubbard & Swedberg, 2012, p. 4; McNeil & McNeil, 2009, p. 164). When the landing area follows the trajectory of the athlete, EFH will be kept constant throughout the landing region, and thereby insensitive to velocity (McNeil et al., 2012, p. 16; Moore et al., 2021, p. 6). Figure V demonstrates how EFH could be of a constant value regardless of the landing point, with a convex landing area. Therefore, parabolic landing shapes may be advantageous to fit different groups of athletes, as well as changing snow- and weather conditions that may affect velocity (Wolfsperger et al., 2021a, p. 8; 2021b, p. 1084). Budget, however, is a limiting factor since more snow is required to construct a jump with a constant EFH if the terrain doesn't already show a parabolic shape, and real-life jump designs often need to compromise costs and safety.

Hubbard and Swedberg (2012) investigated how uncontrollable factors, such as lift, drag, wind and "pop" affected EFH. Their findings suggests that changes in EFH would be small compared to how much the different variables changed, including air resistance (Hubbard & Swedberg, 2012, p. 11). This strengthens the possibility to standardize jumps. Investigations done on recreational athletes in terrain parks supports this (McNeil, 2012b, p. 8). Common for aerial maneuvers are several rotations, where the athletes often decrease the total frontal areal and thus the moment of inertia, which reduces air resistance. Despite this, McNeil (2012b, p. 8) found that aerial maneuvers on small jump did not affect EFH substantially. However, jumps in Big Air and Slopestyle are often larger than those of terrain parks, and research concerning aerial maneuvers in terrain parks may not be representative to these disciplines. Air resistance may also be affected by wind conditions. While Hubbard and Swedberg (2012, p. 11) saw that a wind strength of six meters per second did not change the EFH much, McNeil (2012b, p. 6) found that a head wind of about 9 m/s affected the velocity to a great extent. The effect ranged from -14,4 % to 8,5 % when heading for a big jump with a takeoff speed of 15 m /s (McNeil, 2012b, p. 6). On jumps smaller than 20 meter, this effect can be neglected, because it don't change the trajectory more than that the accuracy will be within a 10 % level (McNeil, 2012b, p. 6). Since air resistance don't affect the velocity or trajectory much, minimizing the drag and maximizing the lift effect is not as effective in these disciplines to enhance performance as it is in for example Nordic ski jumping (Hubbard & Swedberg, 2012, p. 7). However, more research on air resistance during a maneuver is necessary for Big Air and Slopestyle.

3.5.4 Speed as an injury risk factor in landing

During landing, especially snowboarders suffer whiplash injuries (Steenstrup et al., 2018, p. 4). Such injuries are caused when the snowboarder catch the back edge of the board after landing (Steenstrup et al., 2018, p. 4). This typically results in a continuous rotation forward of the trunk, ending with an impact of the head. The impact to the head in this type of fall is dependent on the component of the velocity that acts parallel to the surface an in the direction of the travel. The relationship between linear velocity and angular velocity can be explained by the equation:

$$v_p = \omega * r$$

where v_p is the linear velocity parallel to the surface, ω is the angular velocity of the forward rotation of the trunk and r is the distance from the ground to the head. The magnitude of the velocity that works parallel to the surface is transferred to the angular velocity around the board edge and determines the impact to the head along with the lever arm (r). However, this velocity component will only be relevant in events where there is a catch on the back edge of the board or similar situations which luckily are quite seldom (Steenstrup et al., 2018, p. 4). This injury risk factor has not been included in this project, due to inadequate data on such events.

3.5.5 Competition format as an injury risk factor

An interesting factor to consider, can be the situation in which the run is performed. Qualifications may differ from finals, depending on the tactical choices of the athletes. Some athletes give it all in qualification to secure a spot in the finals, while others save their most advanced and risky maneuvers to the finals. Also, it can be challenging to maintain a high altitude throughout all three jumps in a Slopestyle competition. The longer the airtime is on one jump, the less time the athlete has to develop velocity for the next jump. This requires planning and regulation of velocity. Misinterpretation of the course and velocity demands might lead to landings in areas that exposes the athlete to great forces.

3.6 Sex differences

It is important to specify that sex is used as a proxy for all factors that might affect differences in landing outcome between male and female athletes. From previous studies, it is known that male have more mass compared to female sex (Janssen et al., 2000, p. 83; Schorr et al., 2018, p. 4), which may increase takeoff velocity. Furthermore, research reveals that male sex also has a higher muscle to mass ratio compared to female sex (Janssen et al., 2000, p. 83; Schorr et al., 2018, p. 3), which enhances their ability to "pop", and to control the landing impact. Body Mass Index (BMI) might provide an indirect picture of muscle to mass ratio, with the assumption that World Cup athletes are in good physical shape, and that a higher BMI are explained by a higher muscle mass, and not obesity. Psychological factors may differ between sex as well, resulting in different levels of motivation and risk taking (Breivik et al., 2017, p. 268; Cross et al., 2013, p. 2; Rugg et al., 2021, p. 3).. Higher competition among male athletes for example, might result in more training hours and thusly a higher level compared to female athletes, beyond what can be explained by differences in muscle strength or body weight. Consequently, the sport and the difficulty of maneuvers may evolve in different rates for male and female athletes.

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Article

***Title**: A biomechanical analysis of how rider behavior and equivalent fall height affect landing stability in World Cup Slopestyle for freeski and snowboard.*

Abstract

Purpose*:** The purpose of this project was to investigate different rider behavioral factors along with Equivalent Fall Height (EFH), to see how they affected landing stability for World Cup Slopestyle athletes on freeski and snowboard. Landing stability was used as a surrogate measure of injury risk. ***Methods*:** The data was collected from a Slopestyle competition in Seiser Alm, using a geodetic video method. 3-dimensional models of the athletes' center of mass trajectories were reconstructed, so physical parameters such as EFH could be calculated. Further, a qualitative assessment of landing stability and rider behavioral factors was done, including average angular velocity (ω_{avg}), axial motions, and rider orientation during landing. Landing stability was classified as "good" or "bad", and logistic regression with landing stability as the dependent variable were used to calculate probability of bad landing stability with different values of EFH and rider behavioral factors. ***Results: Snowboarders showed bad landing stability twice as often as skiers, which can be explained by elementary differences in attachment to equipment and range of motion. EFH significantly increased probabilities of bad landing stability for skiers and snowboarders, while ω_{avg} significantly increased probabilities of bad landing stability for snowboarders. Skiers showed an interaction effect between ω_{avg} and axial motions, where monoaxial maneuvers showed higher probabilities of bad landing stability compared to multiaxial maneuvers on high ω_{avg}. This can be caused by a higher proportion of the ω_{avg} around one axis, and not distributed around several axes. Switch landings significantly increased the probability of bad landing stability for snowboarders, but not for skiers. ***Conclusion***: For skiers, increased EFH values, along with high ω_{avg} in monoaxial maneuvers showed the highest probabilities of bad landing stability. For snowboarders, increased EFH values, together with increased ω_{avg} and switch landings gave the highest probabilities of bad landing stability. This means that rider behavior impacts landing stability, which emphasizes that keeping EFH values low is important.

Introduction

Big air and Slopestyle are snowboard and freeski disciplines where the athletes carry out different aerial maneuvers on big jumps. While Big Air only consist of one jump, Slopestyle consists of a region with terrain park elements, such as rails and boxes, and a region with big jumps. In competitions, the athletes' scores are determined by the complexity of the maneuvers they perform. Five different criteria are equally considered: variety, difficulty, execution, amplitude, and progression. Difficulty describes the complexity of maneuvers, and include the number and direction of rotations, the height of the performed jump and the risk taken among other things (Fédération Internationale de Ski, 2019, p. 13). This implies that the jumps need to be of a certain size to provide enough airtime for the athletes to do advanced maneuvers. Recently, Big Air and Slopestyle have been included in the Olympics. Slopestyle for both freeski and snowboard came on the agenda in 2014, Big Air for snowboard in 2018 (International Olympic Committee, 2021a, 2021b), while Big Air for freeski first entered the games in Beijing 2022 (The Beijing Organizing Comittee, n.d.) .

Since the entrance of Slopestyle and Big Air in the Olympics, a high injury rate was observed (Palmer et al., 2021, p. 2; Ruedl et al., 2012, p. 2; Soligard et al., 2019, p. 3; Soligard et al., 2015, p. 2; Steffen et al., 2017, p. 2). Studies show that knee injuries are common among elite athletes in these sports (Flørenes et al., 2010, p. 806; Major et al., 2014, p. 4; Steffen et al., 2017, p. 2; Torjussen & Bahr, 2005, p. 375; 2006, p. 232), and that injury prevalence is also high for head, chest and spine (Steenstrup et al., 2014, p. 4; Torjussen & Bahr, 2005, p. 375). When drawing lines to recreational skiers and snowboarders in terrain parks, one has seen that in addition to the head, injuries to the upper extremity are common (Carús & Escorihuela, 2016a, p. 417; Moffat et al., 2009, p. 260; Russell et al., 2013, p. 175). This particularly applies to the shoulders and wrists (Carús & Escorihuela, 2016a, p. 417; Russell et al., 2013, p. 175). Injuries to the upper extremity happen with elite athletes as well, but more rarely (Major et al., 2014, p. 4; Steffen et al., 2017, p. 2; Torjussen & Bahr, 2005, p. 375; 2006, p. 232).

In terrain parks, poor construction of jumps and falling from heights are highly related to injuries. In fact, jumps are the terrain park feature in ski resorts that shows the highest rate of injury (Carús & Escorihuela, 2016a, p. 417; Flørenes et al., 2010, p. 806; Major et al., 2014, p. 4; Russell et al., 2013, p. 174; Tarazi et al., 1999, p. 178). Due to this, two ski areas Audet et al. (2021) studied, removed jumps from terrain parks hoping to reduce the high injury rate. With the absence of jumps in the park, they found a decrease in severe injuries. However, the rate of injury increased again after three seasons. For athletes competing in freestyle sports, the exhilaration and thrill induced by the activity is often important. It can be thought that users of jumps in terrain parks started going to other ski resorts to obtain that exhilaration, or that they adapted to the jump-less terrain parks and started doing airborne maneuvers on other features which were not designed for it (Audet et al., 2021, p. 214). This might indicate that the athletes seek out the rush they get from jumps despite the higher risk of injuries. Consequently, jump design should not only aim to reduce the risk of injuries, but also maintain the athletes' need to experience exhilaration.

After performing a jump, the athlete is exposed to reaction forces from the ground that need to be absorbed during landing. Landing impact on the athlete, depends on the deceleration of the athlete's velocity component that works perpendicular to the surface. The amount of energy that needs to be absorbed during landing may result in injuries (Swedberg & Hubbard, 2012, p. 122). Equivalent Fall Height (EFH) was introduced to translate the impact energy into a measure one can relate to. EFH expresses the impact energy as the height that would correspond to the impact if the athlete would fall onto a horizontal (Hubbard et al., 2009, p. 178; Hubbard & Swedberg, 2012, p. 3; McNeil et al., 2012, p. 6). EFH is determined by the speed and direction the athlete has at take-off, since these define the initial conditions of the flight trajectory. "Pop" is a factor that is hard to predict if wanting to calculate the athlete's trajectory. "Pop" is when athletes alter their takeoff velocities from what the kicker design would provide, through muscular work. Furthermore, during flight, gravity and aerodynamic forces continuously alter the direction and magnitude of the velocity vector. The latter are influenced by anthropometrics, posture, and equipment (Wolfsperger et al., 2021a, p. 8; 2021b, pp. 1084-1085), but also by external factors such as weather and wind. EFH is therefore dependent on the direction and magnitude of the velocity vector at landing, and the angle to the landing surface. More specifically, EFH is the normal component of the athlete's velocity vector onto the snow surface ($V_|$) and can be calculated with the equation $EFH = \frac{v_|^2}{2g}$ (Hubbard & Swedberg, 2012, p. 3; Swedberg & Hubbard, 2012, p. 122). Therefore, in order to predict the athletes' landing impact, the difference in anthropometry, and uncontrollable factors such as riders "pop", snow-friction and weather conditions need to be included in the prediction models.

The body of scientific literature on jump design related to risk of injury is substantial (Böhm & Senner, 2008; Hubbard et al., 2009; Hubbard & Swedberg, 2012; Levy et al., 2015; McNeil, 2012a, 2012b; McNeil et al., 2012; McNeil & McNeil, 2009; Moore et al., 2021; Swedberg & Hubbard, 2012), and one important finding is that the angle of the landing surface should match the angle of the athlete's trajectory at touch down to minimize EFH (Hubbard et al., 2009, p. 178; Levy et al., 2015, p. 230; McNeil et al., 2012, p. 6; Swedberg & Hubbard, 2012, p. 122). Some jump designs result in smaller values of EFH, and this might avoid severe injuries due to the reduction of impact in landings (McNeil et al., 2012, p. 9; Moore et al., 2021, p. 6). High values of EFH typically occur for landings on flat areas, such as on the knuckle, or the bucket (McNeil & McNeil, 2009, p. 160). Studies show that EFH increases linearly with the horizontal distance of the jump (Moore et al., 2021, p. 6; Swedberg & Hubbard, 2012, p. 133). An ideal landing in a standard Table-top jump, would be in the "sweet spot", which lays approximately two meters after the knuckle (McNeil, 2012a, p. 5). Here, the impact would be the smallest (Kulturdepartementet, n.d.; McNeil et al., 2012, p. 7). The United States Terrain Park Council (USTPC) recommends that no jumps should have a landing with an EFH value of more than 1,5 meters (McNeil et al., 2012, p. 8).

Because jumps and falling from heights are frequent injury situations in terrain parks (Carús & Escorihuela, 2016a, p. 417; 2016b, p. 87; Moffat et al., 2009, p. 260; Russell et al., 2013, p. 172; Russell et al., 2014, p. 3), instability in landing can be thought of as an event that can be counted as surrogate measure of injury risk in jump landings. In a similar sense, instability have been related as a surrogate measure to the moment before falling in ski-cross (Bakken et al., 2011, p. 1317; Randjelovic et al., 2014, p. 5). In injury risk investigations, the number of injury incidences is typically small, which weakens statistical power (Kröll et al., 2017, p. 1644). Increasing the sample size seems unrealistic and unethical. Therefore, statistical power can be increased by using so called surrogate measures, where not only actual injuries are included, but also events that frequently have been related to the injuries and act as predictors of potential injury situations. The surrogate measure approach is typically seen as a valid measure and therefore used to investigate small populations (Kröll et al., 2017, p. 1645).

Rider behavior during the airborne phase might also impact injury risk. The maneuvers with rotations in different axes, the direction of rotations and the orientation of the athletes during takeoff and landing might influence the landing outcome in terms of stability and control (McNeil et al., 2012, p. 4). Because of this, one may think that maneuvers that enhance performance through increased complexity, increase injury risks. Few studies have investigated rider behavior on jumps, and how that impact injury incidence. Kurpiers et al. (2017) did an observational assessment of rider behavior to predict mechanisms of fall for snowboarders. They saw that landing on flat areas and doing spin-maneuvers had significant predictive relationships to falling (Kurpiers et al., 2017, p. 2459). It is important to investigate rider behavior along with EFH, to fully understand how jump design and athlete behavior relate to injuries.

The investigation of Kurpiers et al. (2017) was done in a Terrain Park and included only snowboarders. There are two groups competing on the same jumps in competitions, skiers, and snowboarders. An important factor that distinguishes these groups from each other, is how snowboarders are attached with both feet to the board, giving them reduced degrees of freedom and limited range of motion compared to skiers. According to Harbourne and Stergiou (2003, p. 375), a decrease in degrees of freedom enhances stability, but complexity is reduced. Complexity is preferable in situations where a rapid change of strategy to perform a task is necessary (Stergiou et al., 2006, p. 128). Maintaining balance on uneven snow surfaces can be such a situation. Consequently, snowboarders have reduced capacity to compensate for instability. Due to differences between the groups, one cannot assume that variables affect landing stability for skiers and snowboarders in the same way.

Research questions and hypotheses

This thesis is a part of a bigger ongoing project. The International Olympic Committee (IOC) have initiated a project to assess how injury risk can be reduced in Big Air and Slopestyle. The aim of the project is to provide scientists and practitioners with knowledge that allows them to build jumps that are safe, but also maintain the exhilaration for the athletes using them. By investigating rider behavior along with EFH on the same jumps, one can get an indication whether jump design is the only parameter to consider when the aim is to reduce injury risk, or if some of the variance in landing stability can be caused by the actions of the athlete.

In this project, landing stability was used as a surrogate measure of injury risk, and the aim was to investigate how EFH and rider behavior impact landing stability in Slopestyle athletes. Because of the desire to maintain a simple model without too many complicated effects, only rider behavioral factors that happened after leaving the takeoff were included, and it was assumed that all went well until the athlete was airborne. Prediction models are made for skiers and snowboarders separately.

Main effects

Based on findings from existing research, the impact in the landing is a central source of injury (Hubbard et al., 2009, p. 182; McNeil et al., 2012, p. 9; Moore et al., 2021, p. 6), if assuming that the kicker is ideally shaped, and that the athlete is sent airborne with control. Thusly, a high EFH is a factor that causes instability for male and female skiers and snowboarders upon landing. The first hypothesis of this thesis was therefore necessary to establish the impact EFH has on landing stability.

H_1: EFH have a negative impact on landing stability for Slopestyle athletes on freeski and snowboard.

Regarding rider behavioral factors that occurs after leaving the takeoff, three variables were assumed to increase complexity and affect landing stability: Average angular velocity (ω_{avg}), axial motions, and rider orientation during landing. ω_{avg} decides how fast the athlete rotates around his own axes during a maneuver. Kurpiers et al. (2017, p. 2459) found no clear relationship between degrees in a maneuver and fall incidence. However, by only comparing degrees, differences in airtime might cover up the effects. ω_{avg} might therefore be better suited for comparison. Assumably, a higher ω_{avg} gives the athlete less time to orient oneself before landing, which can result in either over- or under rotation and thus instability. The second hypothesis investigated therefore the relationship between ω_{avg} and landing stability.

H_2: ω_{avg} have a negative impact on landing stability for Slopestyle athletes on freeski and snowboard.

Axial motions define how the body of the athlete is oriented relatively to the snow surface. It can be assumed that a maneuver with multiple axes will increase the risk of injury because the athlete needs to orient oneself before landing and adjust oneself in multiple directions to secure a stable landing. This led to the third hypothesis being:

H_3: Multiaxial maneuvers have a negative impact on landing stability for Slopestyle athletes on freeski and snowboard.

Furthermore, landing stability might be reduced if the athlete has limited perception over the landing area, which is the case for skiers landing switch. Switch rider orientation refers to when the skier is oriented in the opposite direction as the velocity vector. In fact, studies have been done on landing impact and rider orientation (Löfquist & Björklund, 2020). They saw no difference in landing force between switch and normal landing for skiers after a 180 jump (Löfquist & Björklund, 2020, p. 1567). However, they claimed to observe a biomechanical difference between landing normal and switch. During normal landing, the athlete seemed to have greater flexion in the knees with a more upright posture of the upper body (Löfquist & Björklund, 2020, p. 1569). Assuming that a biomechanical difference exists, it can be thought to affect landing stability. Switch rider orientation for snowboarders is when they are riding with their dominant front foot in the back. No biomechanical difference can be assumed to exist between landing normal or switch for snowboarders. However, how accustomed the athletes are at landing switch can affect landing stability, with the assumption that the skills to overcome perturbations to the snow surface and maintain stability is better for normal compared to switch landing orientation. The firth hypothesis was:

H_4: A switch rider orientation during landing have a negative impact on landing stability for Slopestyle athletes on freeski and snowboard.

Lastly, the ability of overcoming a given force assumably increases with the increase in strength. In this project, there was an assumption that male athletes have a higher muscle to mass ratio compared to female athletes (Janssen et al., 2000, p. 83; Schorr et al., 2018, p. 3). Sex further acted as a proxy for other factors that could not be measured, such as psychological factors. Because of that, male athletes were hypothesized to impact landing stability.

H_5: There is a difference in landing stability between male and female athletes.

Interaction effects

When dealing with several factors that may influence the outcome, it can be thought that some variables interact with each other. For this project, a possible interaction was that axial motions moderated the impact ω_{avg} had on landing stability. If only rotating around one axis, the impact on landing stability might be smaller on a given ω_{avg} compared to having the same ω_{avg} but rotating around multiple axes. Hypothesis 6 explains this relationship:

H_6: Multiaxial maneuvers moderate the impact ω_{avg} has on landing stability for Slopestyle athletes on freeski and snowboard.

Another interaction effect might be how sex moderate the impact ω_{avg} has on landing stability. In this hypothesis there is an assumption that male athletes more frequently perform maneuvers that they might not fully manage to do. This can be explained by speculations that male athletes are more risk seeking (Breivik et al., 2017, p. 268; Cross et al., 2013, p. 2), and how higher competition requires a higher skill level for male athletes. Since one of the variables that can be altered with an aim to advance maneuvers is ω_{avg}, sex might moderate the impact ω_{avg} has on landing stability.

H_7: Male athletes moderate the impact ω_{avg} has on landing stability for Slopestyle athletes on freeski and snowboard.

Methods

Subjects

A total of 172 subjects distributed between male and female athletes on freeski and snowboard participated in this project. Inclusion criteria were elite level in Slopestyle, and participation in World Cup events. Height (cm) and mass (kg) were collected prior to the competitions in Seiser Alm. Clothes and equipment as skis, boots, etc. were included, to include the true mass of the athletes. Body Mass Index (BMI) was calculated as $BMI = mass\ (kg) / height^2\ (m)$. Subjects were informed about the project and had given their written consent prior to the data collection.

Ethical considerations

Since this thesis is a part of a bigger ongoing project, this investigation follows ethical guidelines and have been approved by the ethical committee at the Norwegian School of Sports Sciences, and the Norwegian Centre of Research Data with application IDs:

- Norwegian School of Sports Sciences Ethical Committee: Søknad 11-130617 – Utvikling av en valid verktøy for Samuelson av hopp konstruksjon i Slopestyle og Big Air.
- Norwegian Centre for Research Data: USD – Utvikling av en valid verktøy for simulasjon av hopp konstruksjon i Slopestyle og Big Air.

Data collection

The data collection took place in a Slopestyle World Cup competition in Seiser Alm in March 2018. The videos were used for calculation of physical parameters, and observational assessment of rider behavior. A total of 1321 jumps, distributed between three jumps placed in a row in the Seiser Alm Slopestyle course, was recorded from qualifications and finals, using a geodetic video method. In Figure 1, one can see the tachy-meter based camera system, and the three consecutive jumps.

Figure 1. *Pictures from the data collection in Seiser Alm. The upper left photo shows the tachy-meter based camera system, while the other two show the consecutive jumps.*

Measurement instruments

The data was collected using the QDaedalus surveying method (QDaedalus, Geodesy and Geodynamics, ETH Zurich, Zurich, Switzerland). The system consists of two total stations of the type Leica Tachymeter (Leica Total Station T1800, Leica Geosystems AG, Heerbrugg, Switzerland), with an attached CCD-camera of the type AVT Guppy F-080C (Allied Vision Technologies), and an external steering mechanism that allows to actively take control of the server motors that steers the horizontal and vertical angles of the total stations telescope orientations. This mechanism allowed to visually track the athletes from the two stations. The stations were placed approximately 300 meters from the course, recording two different perspectives onto the course (Figure 2). 3D-positions of the athletes' trajectories were determined with a forward intersection method between the direction vectors of the QDaedalus. To allow this forward intersection, a local geodetic network, the QDaedalus stations and a reference position were globally positioned using a differential global navigation satellite system. A GPS-receiver of the type ANN-MS-0 (U-blox, Switzerland) was attached to the system to time synchronize the CCD-camera and total station measurements (Hauk et al., 2017, p. 295). The snow surface of the course was captured using a Lidar laser scanning method (Pegasus backpack, Leica Geosystems, Heerbrugg, Switzerland). To measure 3D-wind velocities, two ultrasonic anemometers (Model 8100, R. M. Young Company, United States) were used, recording at 1 Hz.

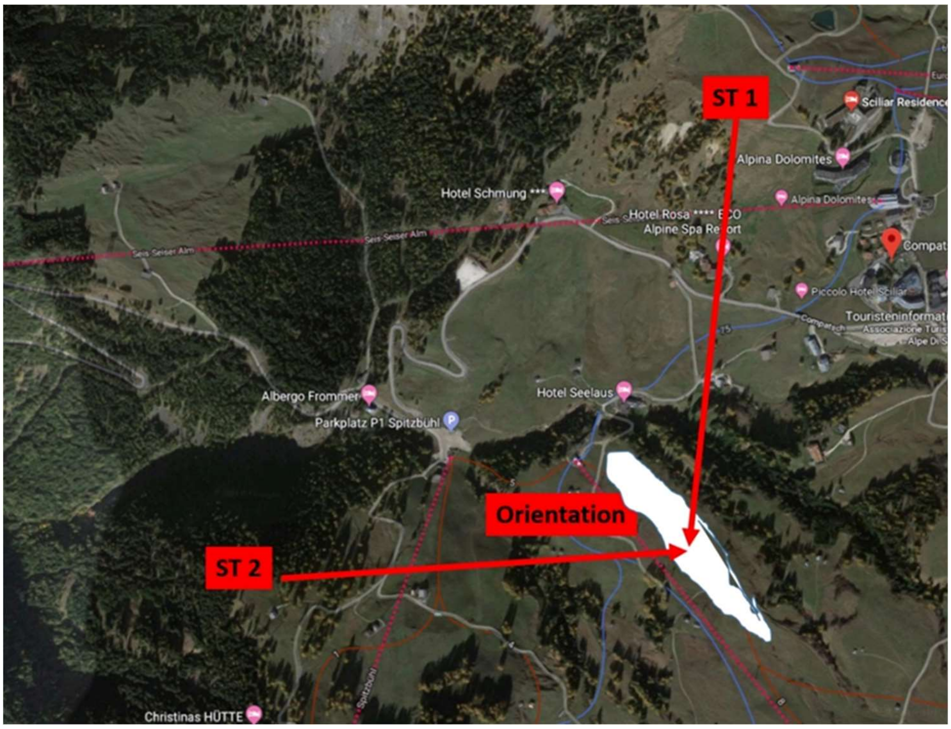

Figure 2. *This picture shows the placement of the two total stations, and their orientation (red lines) relatively to the course.*

Data processing

Physical variables

The images captured with the QDaedalus total stations, were used to locate the athlete's center of mass (CoM) position in the image frame. Computer vision (CV) were applied to automatically annotate the athlete as a posture model. For this purpose, the library of Detectron 2 was used (Github, 2022). A mask was added to decrease the area of the image where the athlete could be present, to avoid background noise to interfere with the targeting of the object. This was done using QDaedalus and MATLAB (MathWorks Inc., Natick, MA, USA). Subsequently, the CV algorithm first detected the athlete in the image. In the second step, a pose estimation algorithm was used to annotate the joint center image coordinates of the athlete, within the area where the athlete was detected. Knowing the joint center location in the images, the athlete's CoM position was located using body segment parameter models (de Leva, 1996, p. 1228).

Due to low contrast, CV had difficulties distinguishing the athlete from the background on the black and white pictures from ST2. Consequently, no videos were completely automatically annotated on the parts where the athletes were jumping. This shortcoming was made up for with manual annotation, using QSecAnalysis software (QDaedalus, Geodesy and Geodynamics Lab ETH Zurich, Zurich, Switzerland). The manual annotations were shared between two persons, and only the apparent CoM was annotated.

The CoM annotations in the images from QDaedalus recordings from ST1 and ST2, along with the GPS time-based time synchronization were used into the forward intersection to locate the CoM of the athlete in 3D space. The forward intersection was based on the position and direction measurements from the two QDaedalus total stations. The vectors through the lenses of the cameras were used to locate the intersection of the camera centers in the image. To adjust for the athlete not being centered in the picture, the number of pixels the CoM was from the image center was counted in x and y direction, to obtain the direction vector to the CoM-position. This was done for all points where there were neighboring observations from both cameras, resulting in 3D-trajectories of the athlete's center of mass. The raw positions of the 3D-trajectory were filtered using a cubic spline filter. The spline filtered trajectories were used to calculate EFH, velocity and distance from takeoff to landing.

The point cloud position data from the Lidar Scanner, scanning the snow surface was globally aligned with the trajectories using passpoints and Helmert transformation. From the transformed digital terrain model data, a profile was extracted. The longitudinal axis of the profile was aligned with the center points of the three consecutive jumps in the course. Figure 3 shows the geometry and measures of the three consecutive jumps. The jumps are divided into four segments: Approach, takeoff (TO), deck and landing area. The angle of the takeoff ($\angle\bar{\theta}$) is calculated from the two last meters of the horizontal distance (x-axis on Figure 3) of the takeoff. The landing angle of the snow surface is calculated over a short distance. This distance centers around the landing point based on the athletes' mean flight trajectory distance per jump.

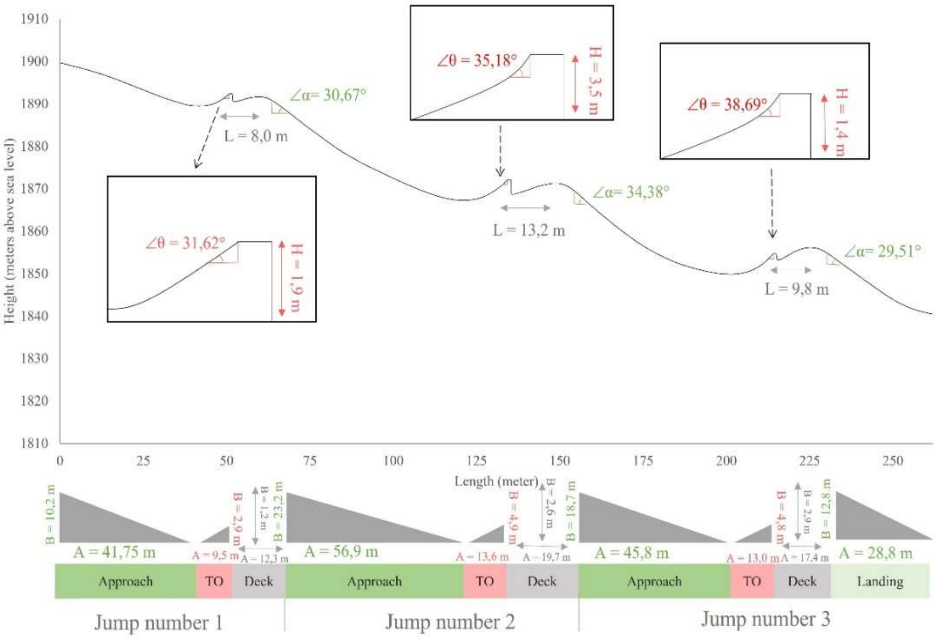

Figure 3. *The geometry and measures of the three jumps in Seiser Alm. Approach/landing has measurements in green, takeoff (TO) has measurements in red, and deck has measurements in grey. A = horizontal distance of segment. B = vertical distance of segment. H = height from deck to takeoff lip. L = length from takeoff lip to highest point on the deck.* $\angle\bar{\alpha}$ *= mean angle of landing area.* $\angle\bar{\theta}$ *= mean angle of takeoff.*

Observational assessment of rider behavior

For the second part of this thesis, different rider variabilities were extracted, using video player software QSecAnalysis and Dartfish 10 ProSuite (Dartfish, Fribourg, Switzerland). Because this project spans over years, two other observers had already evaluated parts of the data set. Coordination of variable definitions were done prior to analyzing the remaining part, with the intention to enhance validity and to secure as little error possible due to different interpretations of the variables between the observers. The most important variables that were observed on video and used in the analyses are listed here. See appendix 1 for a complete list of variables, and the extraction of variables.

Landing quality

Landing quality was assessed as a surrogate measure of injury risk. The low number of true injuries in a competition will not allow to assess injury through counting the number of injuries. By identifying situations where the likelihood for an injury to occur is increased, one can separate situations with increased injury risk from situations with reduced injury risk. By using surrogate measures of injury risk, one accepts a certain level of inaccuracy, since the link between true injury and indication of a situation with increased injury risk is not rigorous. In this thesis the degree of injury risk was measured with events that measured landing quality. Landing quality was firstly assessed with four different landing characteristics: “Good”, “Slight Unbalanced”, “Touch” and “Fall”, as can be seen in perspective 1 in Table 1.

Table 1. *This table presents 3 different perspectives of landing quality. Perspective 1 represents landing event. Perspective 2 represents landing stability, in which the different events are merged into two categories. Perspective 3 represents landing balance and includes “good” from perspective 1 in “balanced”, with the three other events as “unbalanced”.*

Perspective 3	**Balanced**	**Unbalanced**		
Perspective 2	***Good landings***		***Bad landings***	
Perspective 1	*Good*	*Slight Unbalanced*	*Touch*	*Fall*
Explanation	When the athlete landed with control.	If the athlete landed unbalanced, but regained control without much hesitation.	If the athlete landed unbalanced and had to touch the ground with one or two arms to regain balance.	If the athlete fell during landing.

To enhance statistical power, the four categories were merged into two categories of landing stability: “good” and “bad” landing stability, which is shown in perspective 2 in Table 1. Because unbalance is common prior to falling, “slight unbalance” can also be considered an event that could lead to an injury situation. Consequently, landing balance was a third perspective of landing quality, where the events were classified into the categories “balanced” and “unbalanced” (perspective 3 in Table 1).

In this thesis, injury risk incidence was investigated according to both fall incidence, landing stability and landing balance. Fall incidence represented the most accurate classification regarding injury risk but had few cases. Landing balance on the other hand, was the least accurate measure, but had more cases which increased statistical power. Landing stability was in between in terms of accuracy of the measure and statistical power, and were therefore used as the primary outcome measure in the regression analyses.

Average angular velocity (ω_{avg})

Average angular velocity (ω_{avg}) was calculated through the equation:

$$\omega_{\mathrm{avg}} = \frac{\Delta\theta}{\Delta t} = \frac{\theta_1 - \theta_0}{t_1 - t_0}$$

Where $\Delta\theta$ is the sum of the degrees the athlete rotated in the maneuver. $\Delta\theta$ was calculated from the degrees rotated at the start of the rotation (θ_0), which was zero, and the degrees rotated at the end of the rotation (θ_1), divided by the difference in time (Δt) between the time of landing (t_1) and the takeoff time (t_0). The degrees rotated was calculated from the number of rotations counted, from the video footage.

Angular velocity changes throughout a maneuver. To reduce the complexity, it was assumed that the athlete had the same angular velocity through the maneuver, and the variable was therefore referred to as average angular velocity, or ω_{avg}. To find airtime, the observed takeoff- and landing-time were registered. Landing time was defined as the first moment any part of the equipment used touched the landing surface. Unfortunately, Takeoff time seemed to differ between observers. The latter observer defined takeoff time as the last moment when any part of the equipment touched the kicker, while the former observer registered the time when the feet were right above the lip of the takeoff.

This mainly applied to the freeski analyses and led to a systematic error in calculated airtime. By comparing calculated airtime from the two takeoff definitions on 20 videos, a mean difference of 0,04 seconds was observed. Because of this, 0,04 seconds was added to the latest part of freeski analyses.

Axial motions

Monoaxial maneuvers were defined as maneuvers that happened around one axis, while multiaxial maneuvers were executed around two or several axes. Maneuvers were categorized into different tricks, which in turn were classified as either mono- or multiaxial. For both freeski and snowboard, flips and straights were defined as monoaxial. Corks and rodeos were defined as multiaxial, in addition to mistys and bios for skiers and underflips for snowboarders. See appendix 1 for explanation of maneuvers.

Direction of rotation

Backside or frontside rotation for snowboarders were obtained by observation. Frontside rotation is when the athlete rotates from the heel edge, towards the valley. Backside rotation is when the athlete rotates from the toe edge, towards the hill.

Rider orientation

For skiers, information about whether they were riding normal or switch, was obtained by observing which way the athlete was orientated on the takeoff and landing. For snowboarders, it was identified which foot the athlete had in front towards the jump at takeoff. Information about goofy or regular stance were collected prior to competition. With this information, one could figure out if the athlete were riding regular or switch. This information only existed for the runs where the Bib number and start lists were available, so their normal stance could be obtained.

Competition formats and jumps

Competition formats could affect landing stability or complexity of maneuvers. Time information from each video would be matched to start lists and start times, to determine if the run were from qualifications or finals. The videos that lacked a match in start times were defined as training. These runs had limited information about the athlete. Bib-number and sex could not be provided for training runs, as well as stance and rider orientation for snowboarders. How landing quality differed between the three jumps were also of interest. The jumps were defined as jump 1, 2 and 3, ascending from the top to the lowest jump.

Data analysis

Data analysis of the physical variables

Parameters of interest from the 3D-trajectory were mainly the component of the velocity working perpendicular to the ground ($V_|$) during landing to estimate the EFH. Other variables that were used were the mean horizontal distance of the jump, to establish where athletes frequently land, and the takeoff velocity for the discussion of the results.

EFH

The velocity vector of the athlete (V_A) was derived with a central difference method for the entire trajectory. The landing was identified at where the athlete trajectory intersected with a plane that was lifted 0,9 meter above ground. Since EFH depends on the angle of the athlete (θ_A) relative to the angle of the landing (θ_L), these were calculated to establish EFH according to (Hubbard & Swedberg, 2012, p. 3; McNeil et al., 2012, p. 6):

$$EFH = \frac{V_A^2 \, sin^2 \, (\theta_A - \theta_L)}{2g}$$

In this equation, $V_A sin \, (\theta_A - \theta_L)$ refers to the component of the velocity that works perpendicular to the surface.

Data analysis of the observational assessment of rider behavior

Rider behavior described the complexity of maneuvers and landing stability. Complexity of maneuvers were performance measures. Increased complexity was also assumed to reduce landing stability. Landing stability was used as a measure for the degree of injury risk.

Descriptive analysis

Firstly, descriptive were analyzed, to map out differences in group properties, landing qualities, EFH, and rider behavioral factors within and between groups. Differences in landing quality and rider behavior related to different jumps were also investigated, as well as differences in landing quality and rider behavior related to finals, qualifications and training. Male and female athletes compete in separate competitions, and grouping them when doing analyses were natural.

Determination of potential injury risk factors

For the final analyses, the goal was to link EFH with rider behavior and analyze how the different variables affected landing stability. For this thesis, the level of difficulty in a maneuver were determined by the ω_{avg}, and axial motions of a maneuver. In addition, rider orientation during landing were considered to influence the complexity. Analyses were done for all participants together, and for freeski and snowboard separated. In addition, each analysis was controlled for sex.

Statistics

Table 2 shows what statistical methods that were used to investigate differences between the descriptive results.

Determination of potential injury risk

To determine how the different variables impacted landing stability, logistic regression analysis was calculated for skiers and snowboarders separately, with landing stability as the dependent variable. Good landing stability were set as reference value, while logistic regression calculated the odds for bad landing stability with different values of the independent variables. Continuous variables included were EFH and ω_{avg}. Sex, axial motions, and rider orientation during landing were dichotomous variables included in the equation. Female athletes, monoaxial maneuvers and normal landing were set as reference values. For interaction effects, ω_{avg} by axis, and ω_{avg} by sex were tested for both skiers and snowboarders. Multicollinearity and additional interactions between the different variables were also tested.

Table 2. *The statistical methods that were used to test the different variables. The row variables represent the variables of interest, while the columns represent the tests, which were used for the populations described in the cells underneath. Additional rider variabilities include rider orientation, and rotational direction.*

Variables	**Chi Square**	**Independent samples T-test (CI95)**	**One-Way Anova with Post-hoc Bonferroni**
Mass, height, and BMI		Between sexes, and between equipment.	Between subgroups.
Landing Quality	All comparisons.		
EFH		Between sexes, and between equipment.	Between jumps.
Flight trajectory variables		Between sexes, and between equipment.	Between jumps.
Angular Velocity		Between sexes, and between equipment.	Between subgroups and between competition formats.
Axial motions	All comparisons.		
Additional rider variabilities	All comparisons.		

BMI = Body Mass Index, CI95 = Confidence Interval set to a 95% level. EFH = Equivalent Fall Height

Results

Anthropometrics

Table 3 shows comparisons in anthropometrics between populations. Some participants did not share anthropometric data, resulting in absence of anthropometric data from 2 female skiers, 2 male skiers, 3 female snowboarders and 2 male snowboarders.

Table 3. *Mean values and standard deviation (±) of mass (kg), height (cm) and BMI for the different groups. Comparison is done between male and female athletes, skiers, and snowboarders, and between subgroups. BMI is calculated as mass/height^2.*

Group	**Mass (kg)**	**Height (cm)**	**BMI**
Sex			
Male athletes (n=125)	84,12 ± 9,42**	178,12 ± 6,99**	26,46 ± 1,95*
Female athletes (n=47)	69,54 ± 8,03**	165,32± 5,62**	25,43 ± 2,51*
Equipment			
Freeski (n=89)	83,24 ± 11,75**	175,88 ± 9,24	26,81 ± 2,37**
Snowboard (n=83)	76,81 ± 9,44**	173,28 ± 8,04	25,50 ± 1,68**
Subgroups			
Male skiers (n=69)	86,83 ± 9,73 [ab]	178,81 ± 7,81 [a]	27,10 ± 1,95 [b]
Female skiers (n=20)	70,87 ± 9,60 [a]	165,75 ± 6,14 [a]	25,80 ± 3,30
Male SB (n=56)	80,78 ± 7,91 [ab]	177,27 ± 5,77 [a]	25,67 ± 1,64 [b]
Female SB (n=27)	68,57 ± 6,66 [a]	165,00 ± 5,31 [a]	25,15 ± 1,73

[a]=Significant difference p<0,001 (Bonferroni) between sex within equipment, [b]=significant difference p<0,001 (Bonferroni) between equipment within sex
*=Significant difference between populations p<0,05, **=significant difference between populations p<0,001, SB = Snowboarders, BMI = Body Mass Index

Male skiers had a significant higher mass and BMI, compared to male snowboarders (p<0,001) (Table 3). There was no significant difference between male skiers and male snowboarders in height. Between female skiers and snowboarders, there were no significant differences in mass, height, or BMI. Male skiers had higher mass, height, and BMI (p<0,001) compared to female skiers. Male snowboarders also had higher mass and height (<p<0,01) compared to female snowboarders, but with no difference in BMI. There were no significant differences between male and female snowboarders in BMI. Regardless of equipment, male athletes had higher mass, height and BMI compared to female athletes (p<0,001). Skiers showed higher mass and BMI compared to snowboarders (p<0,001), while there was no difference in height.

Landing quality

Table 4 provides an overview over the incidence of fall, bad landing stability, and unbalanced landings. Between male and female athletes, there was no difference in landing quality. Snowboarders had a higher fall incidence, incidence of bad landing stability and an incidence of unbalanced landings, compared to skiers (p<0,001).

Table 4. *This table shows the percentage of fall, bad landing stability, and unbalanced landings. Male and female athletes are compared, and skiers and snowboarders are compared. The incidence of fall is included in bad landings, while the incidence of bad landings is included in unbalanced landings.*

Group	**Fall Incidence**	**Bad landing stability**	**Unbalanced landings**
Sex			
Male athletes	9,8 %	17,4 %	33,1 %
Female athletes	11,8 %	17,1 %	28,9 %
Equipment			
Freeski	5,8 %**	10,1 %**	28,4 %
Snowboard	13,2 %**	22,6 %**	32,7 %

*=Difference between populations p<0,05, **=difference between populations p<0,001

As can be seen in Figure 4, incidence of both fall, bad landings stability and unbalanced landings occurred more often with male snowboarders compared to male skiers (p<0,05). There was also significant higher incidence of fall and bad landing stability for female snowboarders compared to female skiers (p<0,001), but not in unbalanced landings. There were no differences between sexes within equipment in any perspective of landing quality.

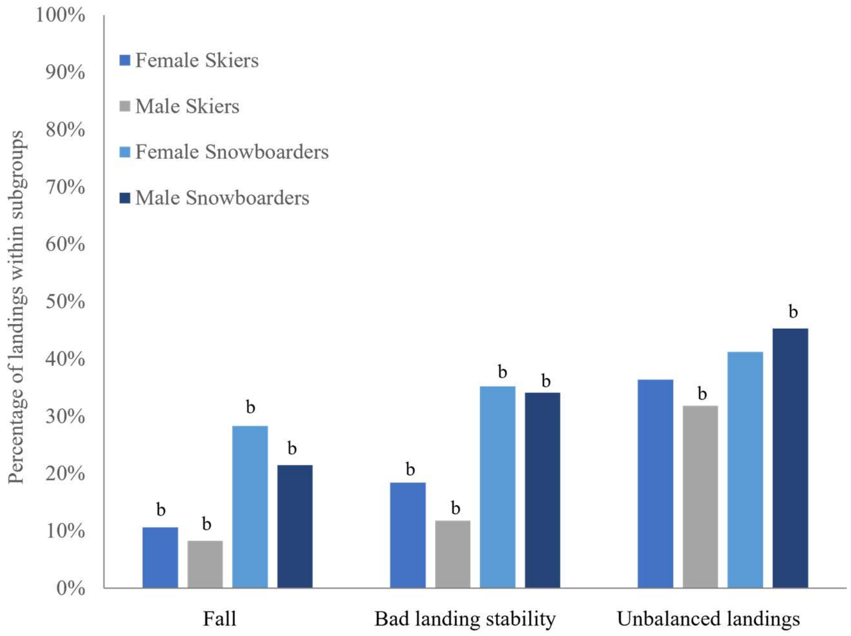

Figure 4*. Show the percentage of falls, bad landings, and unbalanced landings for male skiers, female skiers, male snowboarders, and female snowboarders. b=Difference between equipment within sex P<0,05.*

When differentiating between the jumps, one can see in Table 5 that snowboarders showed a higher percentage of falls and bad landing stability on all jumps compared to skiers (p<0,05). There was no difference between skiers and snowboarders in unbalanced landings for any of the jumps. There were no significant differences between jump 1, 2 and 3 in the percentage of falls for either skiers or snowboarders. Snowboarders had a higher incidence of bad landing stability on jump number 3 compared to jump number 1 and 2 (p<0,05), while jump number 1 showed no significant differences in bad landing stability compared to jump number 2. Snowboarders also had more unbalanced landings on jump 3 compared to jump 2 (p<0,05), with no statistical difference for jump 1 compared to 2 and 3. Skiers showed a lower incidence of bad landing stability on jump 1 compared to jump 3 (p<0,01), and no difference on jump 2 compared to jump 1 or 3. Skiers had fewer unbalanced landings on jump 2 compared to jump 1 and 3 (p<0,05). There were no significant differences in unbalanced landings between jump 1 and 3.

Table 5. *This table show how landing quality differs between the different jumps, for freeski and snowboard, and for male and female athletes. Comparisons was done between skiers and snowboarders, and between male and female athletes, and between the jumps for each population. The values er presented in percentage of all landings on the specific jump for the specific population.*

	Fall		**Bad landing stability**		**Unbalanced landings**	
	Freeski	**SB**	**Freeski**	**SB**	**Freeski**	**SB**
Jump 1	4,5 %*	12,5 %*	7,2 %[b]**	20,3 %[b]**	32,1%[a]	32,8%
Jump 2	5,2 %*	11,5 %*	10 %*	19,4 %[c]*	21,3%[ac]	26,0%[c]
Jump 3	7,9 %*	16 %*	13,6 %[b]**	29,5 %[bc]**	31,9%[c]	40%[c]
	Male	**Female**	**Male**	**Female**	**Male**	**Female**
Jump 1	8,4%	12,7%	15,0%	18,6%	35,3%[a]	32,4%[a]
Jump 2	9,9%	6,5%[c]	17,3%*	9,7%[c]*	26,9%[ac]*	18,3%[ac]*
Jump 3	11,3%	16,5%[c]	20,6%	23,5%[c]	37,4%[c]	36,5%[c]

[a]=Statistical difference p<0,05 between jump 1 and 2, [a]=Significant difference p<0,05 between jump 1 and 2, [b]=significant difference p<0,05 between jump 1 and 3. [c]=significant difference p<0,05 between jump 2 and 3., *=Statistical difference p<0,05 between groups, **=Difference between groups p<0,001. SB = Snowboarders.

Male athletes had a higher incidence of bad landing stability, and unbalanced landings on jump 2 compared to female athletes (p<0,05, Table 5). Other than that, there were no differences in landing quality between male and female athletes on any of the jumps. There was no difference in fall incidence between the jumps for male athletes. Within the groups, male athletes showed no significant difference between the jumps in incidence of fall and bad landing stability, but there were fewer unbalanced landings for male athletes on jump 2 compared to jump 1 and 3 (p<0,05). There were no differences in unbalanced landings for male athletes on jump 1 compared to jump 3. Female athletes showed a higher percentage of falls, bad landing stability, and unbalanced landings on jump 3, compared to jump 2 (p<0,05). Jump 1 showed no significant difference from jump 2 and 3 in incidence of fall, and bad landing stability. Jump 2 showed statistically fewer unbalanced landings for female athletes compared to jump 1 and 3 (<0,05). There was no difference between jump 1 and 3 in unbalanced landings.

Figure 5 shows landing quality for all athletes in respect to each jump.

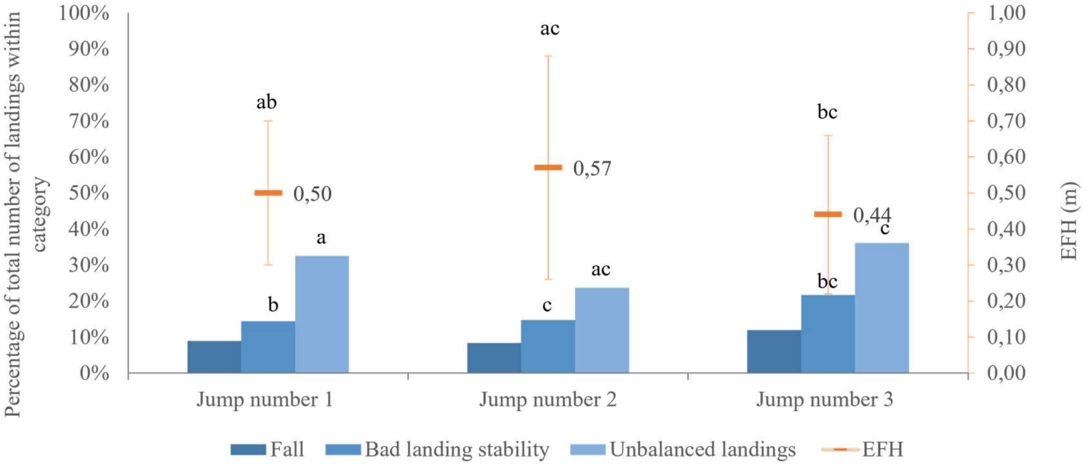

Figure 5. *This figure shows the percentage of fall, bad landings, and unstable landings for jump 1, 2 and 3, on the primary axis to the left. Orange line represents the corresponding mean Equivalent Fall Height (EFH) and standard deviations for jump 1, 2 and 3. Values for EFH is shown on the secondary axis to the right. a=Significant difference p<0,05 between jump 1 and 2, b=significant difference p<0,05 between jump 1 and 3. c=significant difference p<0,05 between jump 2 and 3.*

There was no difference in percentage of falls between the jumps (Figure 5). Jump 3 had a higher incidence of bad landing stability compared to jump 1 and 2 (p<0,05), but there was no difference between jump 1 and 2. Jump 2 had fewer unbalanced landings compared to jump 1 and 3 (p<0,05). There was no difference between jump 1 and 3.

EFH

Figure 5 further show that there is a significant difference between all jumps when it comes to EFH, with jump 2 showing the highest value, and jump 3 showing the lowest value. When assessing EFH for sex, Figure 6 show that there was no significant difference between skiers and snowboarders on any jump. For skiers, jump 3 showed lower EFH compared to jump 1 and 2 (p<0,05), and no significant difference in EFH between jump 1 and 2. Snowboarders had a higher EFH on jump 2 (p<0,05) compared to 1 and 3, while there was no significant difference between jump 1 and 3. Male athletes showed a higher EFH compared to female athletes on jump 1 and 3 (p<0,05, Figure 6), but there was no difference on jump 2. For both male and female athletes, EFH was lower on jump 3 compared to jump 2, while jump 1 did not differ in EFH compared to jump 2 and 3.

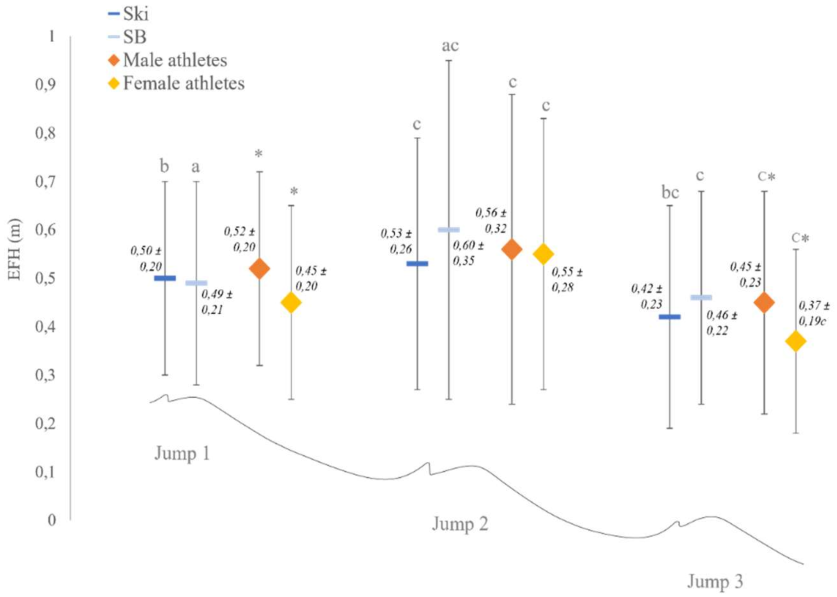

Figure 6. *Overview over differences in mean Equivalent Fall Height (EFH) with standard deviation between male and female athletes, between skiers and snowboarders, and between jumps. a=Significant difference p<0,05 between jump 1 and 2, b=significant difference p<0,05 between jump 1 and 3. c=significant difference p<0,05 between jump 2 and 3. *=Significant difference p<0,05 between male and female athletes. SB=snowboard.*

Physical measures and wind conditions

Firstly, the 3D-velocity of the wind was rather constant, and below 3 m/s for each day. Other physical variables extracted from the 3D-model can be seen in Table 6. For skiers, jump 1 had significantly lower takeoff velocity compared to jump 2 and 3 (p<0,05). There was no difference in Takeoff velocity on jump 2 compared to 3. There were statistically significant differences between jump 1, 2 and 3 in horizontal distance of the jump trajectory for skiers (p<0,05), with jump 2 showing the longest distance, and jump 1 the shortest. For snowboarders there were significant differences between all the jumps in takeoff velocity and horizontal distance of jump trajectory. Jump 2 had the highest values of these variables and jump 1 had the lowest. Only jump 3 showed a difference in takeoff velocity and horizontal distance of jump between skiers and snowboarders (p<0,001).

Table 6. *Additional physical variables from the 3D-model. These values represent mean values with standard deviations of each jump, and comparisons are done between freeski and snowboard, and male and female athletes.*

	Takeoff velocity (m/s)		**Horizontal distance of jump trajectory (m)**	
	Freeski	**SB**	**Freeski**	**SB**
Jump 1	11,34 ± 0,65^{ab}	11,31 ± 0,75^{ab}	16,62 ± 2,46^{ab}	16,97 ± 2,35^{ab}
Jump 2	14,49 ± 0,74^{a}	14,47 ± 0,80^{ac}	22,64 ± 2,89^{ac}	22,09 ± 2,58^{ac}
Jump 3	14,57 ± 1,35^{b}**	14,05 ± 0,75^{bc}**	20,18 ± 2,72^{bc}**	18,25 ± 2,70^{bc}**
	Male	**Female**	**Male**	**Female**
Jump 1	11,45 ± 0,69^{ab}*	11,07 ± 0,64^{ab}*	17,36 ± 2,41^{ab}**	15,51 ± 1,82^{ab}**
Jump 2	14,55 ± 0,81^{a}*	14,32 ± 0,64^{a}*	22,78 ± 2,85^{ac}*	21,64 ± 2,30^{ac}*
Jump 3	14,34 ± 0,89^{b}	14,49 ± 1,79^{b}	19,80 ± 2,90^{bc}*	18,50 ± 2,19^{bc}*

^{a}=Significant difference p<0,05 between jump 1 and 2, ^{b}=significant difference p<0,05 between jump 1 and 3, ^{c}=significant difference p<0,05 between jump 2 and 3, *=significant difference p<0,05 between populations, **=significant difference p<0,001 between populations. SB = Snowboard.

Male athletes had higher values in takeoff velocity and horizontal distance of jump trajectory compared to female athletes on all jumps, except for takeoff velocity on jump 3 (p<0,05) (Table 6). For both male and female athletes, takeoff velocity was lower for jump 1 compared to jump 2 and 3 (p<0,05). There was no difference between jump 2 and 3. Regarding horizontal distance of jump trajectory, all jumps differed from each other significantly for both male and female athletes, with jump 2 showing the longest distance followed by jump 3, then jump 1 ($p<0,05$).

Rider behavior

Regarding behavioral factors, Table 7 show that male athletes in both freeski and snowboard had higher values in both airtime, ω_{avg}, and axial motions compared to female athletes ($p<0,05$). Skiers also had higher values in ω_{avg}, airtime and axial motions compared to snowboarders ($p<0,001$). Same trends as above were seen when looking at subgroups and comparing equipment within sex, except that male skier showed no difference in airtime compared to male snowboarders.

Table 7. *Rider variabilities that affect complexity in maneuvers. Comparisons are done between skiers and snowboarder, between male and female athletes, and between subgroups. Airtime and ω_{avg} are presented in mean values with standard deviation. Axial motions are presented as the percentage of maneuvers within population that were performed multiaxial.*

Group	**Airtime (s)**	ω_{avg} **(°/s)**	**Axial motion (%)**
Sex			
Male athletes	2,05 ± 0,21**	460 ± 140**	70,6**
Female athletes	1,83 ± 0,23**	286 ± 112**	29,6**
Equipment			
Freeski	2,02 ± 0,22**	447 ± 148**	79,8**
Snowboard	1,94 ± 0,25**	349 ± 166**	34,1**
Subgroups			
Male skiers	2,07 ± 0,21 ^{a}	493 ± 131 ^{ab}	92,7^{ab}
Female skiers	1,89 ± 0,20 ^{ab}	314 ± 89^{ab}	42,9^{ab}
Male SB	2,04 ± 0,22 ^{a}	421 ± 141 ^{ab}	44,4^{ab}
Female SB	1,76 ± 0,24 ^{ab}	254 ± 127 ^{ab}	15,0^{ab}

^{a}=Significant difference $p<0,001$ (Bonferroni) between sex within equipment, ^{b}=significant difference $p<0,001$ (Bonferroni) between equipment within sex. **=Difference between populations $p<0,001$ SB = Snowboarders.

For additional rider behavioral factors, Table 8 gives an overview over variabilities for skiers and snowboarders separately. Male skiers showed no difference in takeoff orientation compared to female skiers, while male snowboarders rode switch at takeoff more often compared to female snowboarders (p<0,05). Male athletes on both freeski and snowboard seem to land switch more often compared to female athletes (p<0,05). There was no significant difference between male and female snowboarders in the direction of rotation.

Table 8. *An overview over additional behavioral factors for male and female skiers and snowboarders. Comparisons were done between male and female athletes. Because riding switch differs in technique for snowboarders and skiers, these variables are not compared across equipment. Values are presented in percentage of all maneuvers performed within population.*

Groups	**Freeski**		**Snowboard**	
	Male	**Female**	**Male**	**Female**
Rider orientation at Takeoff				
Switch (%)	40,9	32,2	47,5*	31,6*
Rider orientation at Landing				
Switch (%)	51,7*	38,1*	47,8**	15,0**
Direction of rotation (SB)				
Frontside rotation (%)	-	-	52,8	55,6

*=Significant difference between male and female athletes p<0,05, **=significant difference between male and female athletes p<0,001. SB=Snowboarders.

Competition situational factors

Regarding differences in landing quality dependent of competition format, Table 9 show that during trainings athletes have significantly lower incidence of fall and bad landing stability compared to qualifications and finals (p<0,05), while there were no differences between finals and qualifications. There was no difference in unbalanced landings between trainings and finals, but qualifications showed significantly more unbalanced landing compared to finals and trainings (p<0,05). Between female and male athletes, there were no statistical difference in landing quality concerning competition format. Apart from male athletes showing more unbalanced landings in qualifications compared to finals, no difference was observed in landing quality between finals, qualifications, and training within sex.

Table 9. *A table of landing quality in finals (F), qualifications (Q), and training (T). Values are presented in percentage of landings within population for each landing quality. Comparisons are done between male and female athletes, between freeski and snowboard, and between different competition formats.*

	Fall		**Bad landing stability**		**Unbalanced landings**	
F	9,4 %		17,0 %		24,5 %[a]	
Q	11,0 %[c]		18,1 %[c]		35,0 %[ac]	
T	6,7 %[c]		13 %[c]		25,1 %[c]	
	Freeski	**SB**	**Freeski**	**SB**	**Freeski**	**SB**
F	5,8 %*	13,4 %*	6,5 %**	28,3 %[b]**	13,8[a] %**	36,2 %[b]**
Q	6,4 %**	16,4 %[c]**	11,2 %**	26,1 %[c]**	34,2 %[a]	35,9 %[c]
T	2,6 %	8,1 %[c]	10,5 %	13,9 %[bc]	23,7 %	25,6 %[bc]
	Male	**Female**	**Male**	**Female**	**Male**	**Female**
F	9,6 %	9,2 %	18,5 %	13,8 %	25,8 %[a]	21,8 %
Q	10,3 %	13,0 %	18,0 %	18,7 %	36,2 %[a]	32,1 %

[a]=Significant difference between finals and qualification p<0,05, [b]=significant difference between finals and training p<0,05, [c]=significant difference between qualification and training p<0,05, *=significant difference between populations p<0,05, ** =significant difference between populations p<0,001. SB = snowboard, F=finals, Q=qualifications, T=training.

Snowboarders had a higher incidence of fall, bad landing stability and unbalanced landings compared to skiers in finals (p<0,05), and a higher incidence of fall and bad landing stability in qualifications (p<0,05) (Table 9). There was no difference between skiers and snowboarders in landing balance in qualification, or landing quality during training. For skiers, there were no differences in the incidence of fall and bad landing stability between different competition formats. For unbalanced landings, qualifications showed a higher incidence compared to finals (p<0,05), while training showed no difference compared to finals and qualifications. Snowboarders had lower incidence of bad landing stability and unbalanced landings in trainings compared to finals and qualifications (p<0,05). There was no difference between finals and qualifications. There was also less falls for snowboarders in training compared to qualifications, but there was no difference for finals compared to qualifications or training.

Table 10 presents rider behavior according to finals, qualifications, and trainings. Skiers have a higher ω_{avg} and a higher percentage of multiaxial maneuvers compared to snowboarders in both finals, qualifications, and trainings (p<0,05). Skiers showed a higher airtime compared to snowboarders in trainings (p<0,05), while there were no differences in airtime between skiers and snowboarders in finals or qualifications. For skiers there was a statistical difference in airtime between finals, qualifications, and training (p<0,05). Skiers had higher values of ω_{avg} in finals, compared to qualifications and training (p<0,05), but there was no statistical difference in ω_{avg} for skiers between qualifications and training. Further, there were no statistical differences between finals, qualifications, and training in the percentage of multiaxial maneuvers.

Table 10. *Rider behavior according to finals (F), qualifications (Q), and training (T). Airtime and ω_{avg} are presented in mean values with standard deviations. Axes are presented as the percentage of maneuvers within group that were performed multiaxial.*

	Airtime (s)		**ω_{avg} (°/S)**		**Multiaxial (%)**	
	Freeski	**SB**	**Freeski**	**SB**	**Freeski**	**SB**
F	2,15 ± 0,27^{ab}	2,12 ± 0,28^{ab}	496 ± 143^{ab*}	468 ± 141^{ab*}	79,3 %**	56,7 %^{ab**}
Q	2,06 ± 0,22^{ac}	2,05 ± 0,26^{ac}	444 ± 131^{a**}	382 ± 150^{ac**}	80,2 %**	47,6 %^{ac**}
T	1,96 ± 0,23^{bc*}	1,86 ± 0,21^{bc*}	422 ± 188^{b**}	288 ± 172^{bc**}	78,9 %**	25,7 %^{bc**}
	Male	**Female**	**Male**	**Female**	**Male**	**Female**
F	2,22 ± 0,24^{a**}	1,98 ± 0,25^{a**}	550 ± 115^{a**}	361 ± 103^{a**}	80,9 %^{a**}	45,6 %^{a**}
Q	2,11 ± 0,22^{a**}	1,90 ± 0,23^{a**}	464 ± 120^{a**}	278 ± 106^{a**}	75,1 %^{a**}	32,7 %^{a**}

^{a}=Significant difference between finals and qualification p<0,05, ^{b}=significant difference between finals and training p<0,05, ^{c}=significant difference between qualification and training p<0,05, *=significant difference between populations p<0,05, **=significant difference between populations p<0,001. SB=Snowboarders, F=Finals, Q=Qualifications, T=Training.

For snowboarders, there were statistical differences between finals, qualifications, and training in airtime, ω_{avg}, and the percentage of multiaxial maneuvers performed ($p<0,05$) (Table 10). From training to qualification, ω_{avg} increased with about 33 percent for snowboarders, with an additional increase of about 23 percent from qualification to finals. Between male and female athletes, male athletes showed higher mean airtime, ω_{avg}, and percentage of multiaxial maneuvers performed, compared to female athletes in both finals and qualifications. ($p<0,001$). Furthermore, there were statistical differences in airtime, ω_{avg}, and the percentage of multiaxial maneuvers between finals and qualifications for both sexes ($p<0,05$).

Table 11 show that there were no differences in percentage of switch orientation on takeoff, for skiers or snowboarders between finals, qualifications, or trainings. Skiers showed no statistical difference between finals, qualifications, and training in rider orientation during landing. Snowboarders had more switch landings in qualifications compared to finals ($p<0,05$). There was no statistical difference in direction of rotations for snowboarders in trainings, finals, and qualifications.

Table 11. *An overview over additional behavioral factors for skiers and snowboarders related to finals, qualifications, and training. Comparisons are done between competition formats. Because riding switch differs in technique for snowboarders and skiers, these variables are not compared across equipment. Values are represented in percentage of all maneuvers within group.*

	Switch orientation Takeoff		**Switch orientation Landing**		**Frontside rotation**	
	Freeski	**SB**	**Freeski**	**SB**	**Freeski**	**SB**
Finals	39,1 %	41,7 %	54,3 %	22,0 %[a]	-	52,9 %
Qualifications	39,1 %	43,5 %	46,9 %	44,6 %[a]	-	53,9 %
Training	34,2 %	-	43,4 %	-	-	51,6 %

[a]= significant difference between finals and qualifications $p<0,05$. SB = snowboarders

Determination of potential injury risk factors

Freeski

Table 12 shows that both EFH, axial motions and sex were significant main predictors of landing outcome. An increase in EFH and multiaxial maneuvers increased the likelihood of bad landing stability to a large extent. Furthermore, if male athletes conducted the maneuver, the chance of bad landing stability was smaller compared to if female athletes did. In addition, there was a significant interaction effect between ω_{avg} and axial motions, and between ω_{avg} and sex. Thusly, main effects of these variables must be interpreted carefully. There was no main effect of ω_{avg}. Rider orientation during landing did not show a main effect either. Predicted probabilities were calculated for different landing outcomes based on different values of the independent variables in Table 12, and they can be seen in Appendix 2. When checking for multicollinearity and other interaction effects between the variables, no significant effects were discovered.

Table 12. *Variables from the model tested with logistic regression for skiers with landing stability as outcome variable. Good landings are coded as 0 and bad landings as 1. These values explain the odds for a bad landing outcome relative to the reference value of the independent variable. If Odds Ratio (OR) = 1, the odds for a bad landing outcome is the same for the test variable (coded 1), as for the reference variable (coded 0). If OR < 0, there is a reduced chance for a bad landing outcome for the test variable compared to the reference variable. If OR > 0, the chance of a bad landing outcome is greater with the test variable compared to the reference variable.*

Variable in equation	**Beta coefficient**	**Odds Ratio (OR)**	**Lower 95%CI**	**Upper 95%CI**
Constant	-5,920	0,003*		
EFH	3,169	23,793**	4,762	118,881
ω_{avg}	0,004	1,004	0,993	1,014
Axial motions	5,226	185,986*	3,945	8767,410
Sex	-7,294	0,001*	0,000	0,140
Rider orientation during landing	0,039	1,040	0,431	2,511
Angular velocity by axis	-0,011	0,989*	0,980	0,998
Angular velocity by sex	0,015	1,015*	1,002	1,027

* = p<0,05 **=p<0,001, EFH = Equivalent fall height, CI = Confidence interval
Reference values = 0, test variables = 1: Sex: Female athletes = 0 / Male athletes = 1, Axial motions: Monoaxial maneuvers = 0 / Multiaxial maneuvers = 1, Rider orientation during landing: Regular orientation during landing = 0 / Switch orientation during landing = 1
Model x^2 (7) = 27,728, p <0,001, Nagelkerke R Square: 0,177

Snowboard

When looking at Table 13, one can see that increased EFH, increased ω_{avg} and switch orientation during landing increased the chance of bad landing stability for snowboarders. Axial motions and sex could not predict landing outcome for snowboarders based on this dataset. There was no interaction effect between ω_{avg} and axial motions. Neither was it for sex and $\omega_{avg.}$ Even though the latter interaction effect were hypothesized, it was not included in the final regression analysis, because it changed the other variables of the regression to a large extent. For snowboard as well, predicted probability of landing outcome based on different values of the independent variables of Table 13 can be seen in Appendix 2.

Table 13. *Variables from the model for snowboarders tested with logistic regression with landing stability as the outcome variable. Good landings are coded as 0 and bad landings as 1. These values explain the odds for a bad landing outcome relative to the reference value of the independent variable. If Odds Ratio (OR) = 1, the odds for a bad landing outcome is the same for the test variable (coded 1), as for the reference variable (coded 0). If OR < 0, there is a lesser chance for a bad landing outcome for the test variable compared to the reference variable. If OR > 0, the chance of a bad landing outcome is greater with the test variable compared to the reference variable.*

Variable in equation	**Beta coefficient**	**Odds Ratio (OR)**	**Lower 95%CI**	**Upper 95%CI**
Constant	-3,728	0,024**		
EFH	2,049	7,763**	2,530	23,823
ω_{avg}	0,006	1,006*	1,002	1,009
Axial motions	0,677	1,968	0,100	38,624
Sex	-1,099	0,333	0,105	1,061
Rider orientation during landing	0,714	2,042*	1,100	3,791
Angular velocity by axis	-0,002	0,998	0,992	1,004

* = p<0,05 **=p<0,001, EFH = Equivalent fall height, CI = Confidence interval
Reference values = 0, test variables = 1: Sex: Female athletes = 0 / Male athletes = 1, Axial motions: Monoaxial maneuvers = 0 / Multiaxial maneuvers = 1, Rider orientation during landing: Regular orientation during landing = 0 / Switch orientation during landing = 1
Model x^2 (6) = 36,673, p<0,001, Nagelkerke R Square: 0,195

Discussion

The main findings for this study, was that increased ω_{avg} and EFH in addition to a switch landing led to the highest probabilities for bad landing stability for snowboarders. For skiers, logistic regression showed that probabilities for bad landing stability had highest values if the athlete did monoaxial maneuvers, with increased ω_{avg} and EFH. Snowboarders fell and had a higher incidence of bad landing stability compared to skiers. Further, jump 2 was the biggest jump and exposed the athlete to the highest mean EFH, but shad fewer unbalanced landings compared to jump 1 and 3.

Comparison of groups

There are fundamental differences between the groups that are compared in this thesis (Table 3). Skiers show a higher mass compared to snowboarders, and male athletes show a higher mass compared to female athletes. This added mass can contribute among other factors to a development of a higher velocity in the approach (Wolfsperger et al., 2021b, p. 7). This is an important factor to consider when building jumps. Male athletes show a higher BMI compared to female athletes, which can be a result of a typical higher muscle to mass ratio in the male sex (Janssen et al., 2000, p. 83; Schorr et al., 2018, p. 3), if assuming that obesity is absent in elite athletes and that the mass of the equipment is increasing linear with body mass. Higher muscle mass can further improve male athlete's ability to pop, as well as resist high forces upon landing. Consequently, a given EFH can affect female athletes to a larger extent in their landing stability compared to male athletes. When looking at the subgroups, the BMI difference mainly concerns skiers, and not snowboarders. However, one can't say anything about muscle mass, since no body scan was taken and BMI was calculated from mass and height, which included equipment. Size and mass of the equipment were not fixed, but roughly increased with body mass and size between athletes, resulting in inaccurate differences of BMI values between groups. Body characteristics were used to consider the comparability between the groups, and play a role in the interpretation of the results.

Landing quality

Landing quality was divided into three perspectives: the proportion of the population that fell, had bad landing stability, and had unbalanced landings. Bad landing stability were considered as the main surrogate measure of injury risk in this thesis, since the number of true injuries typically occurring during a competition week is too small to allow an assessment of actual injury risk (Kröll et al., 2017, p. 1645). The literature on injury incidence mostly reports actual injuries. Obviously, since not all situations with bad landing stability results in injuries, the incidence of bad landing stability will overestimate the actual injury incidence substantially. Thusly, the surrogate measures of injury risk from this study cannot be compared to previous research reporting injury incidences (Carús & Escorihuela, 2016a, p. 417; Torjussen & Bahr, 2005, p. 372). They should rather be interpreted as a measure of likelihood that an injury could occur, and help to distinguish combination of factors that more likely lead to an injury than others. If percentage of falls were chosen instead of bad landing stability as the main surrogate measure of injury risk, this might have resulted in numbers that were closer to actual injury rates. However, falls and bad landing stability changed in the same manner between the jumps (Figure 5), so choosing bad landings as the surrogate measure of injury risk seemed reasonable since the larger number of events increased statistical power. This is not the first study to look at landing stability related to behavioral factors. Kurpiers et al. (2017, p. 2459) investigated fall incidence related to rider behavior. They reported a fall incidence of 20 % of the total dataset, which is higher compared to this investigation. This comparison is rather weak when comparing two different populations: elite athletes in World Cup events and recreational athletes in terrain Parks. To the best of our knowledge, this project is the first to look at landing stability related to rider behavior for elite athletes including skiers. In addition to that, it is the first study to investigate landing stability related to rider behavior along with EFH.

Landing quality between different groups

When looking at landing quality in respect to the different groups (Table 4), there was no difference between male and female athletes. The only exception was that male athletes showed a higher incidence of bad landing stability and unbalanced landings on jump 2, compared to female athletes (Table 5). When relating landing stability to injury risk, this agrees with the finding of Torjussen and Bahr (2005, p. 375), who found no difference between sexes, but also with Carús and Escorihuela (2016b, p. 87) who saw a slight tendency to a higher risk of injury among male athletes. On the other hand, it is contradictive to statistics from Olympic events (Palmer et al., 2021, p. 3; Soligard et al., 2015, p. 2), which might be a more relevant comparison because it involves elite athletes in competition situations and not recreational athletes in terrain parks. Seeing that there were slight differences might be an important finding since that these groups use the same course during competition. What this result doesn't cover however, is what causes these instabilities. Even if the incidence of fall and bad landing stability are similar, this does not mean that the same factors caused the observed instabilities for both male and female athletes.

Snowboarders seem to have falls and bad landing stability twice as often compared to skiers on all jumps (Table 5). Since EFH was relatively low on all jumps with no difference between skiers and snowboarders (Figure 6), course design might not be the primary factor having caused the instabilities for snowboarders. A substantial difference between skiers and snowboarders is that snowboarders have both feet attached to the board, and therefore reduced range of motion and capacity to regain balance compared to skiers. Such limited range of motion reduces degrees of freedom which in turn reduces the capacity to compensate for small events that lead to instability (Stergiou et al., 2006, p. 128). This theory is supported by the fact that there is a smaller gap between skiers and snowboarders in landing balance compared to landing stability and fall incidence (Figure 4). In landing balance, the landing event "slight unbalanced" is included as an unbalanced landing, which covers small instabilities during landing. Skiers may show a larger difference between incidence of bad landing stability and unbalanced landings compared to snowboarders, because they easier could compensate for these instabilities. The same instabilities might have led to bad landing stability or fall for snowboarders.

Relationship between landing quality and EFH in each jump

Jump 3 shows the lowest EFH between the three Seiser Alm jumps (Figure 5). When looking at the jump profile measurements (Figure 3), the slighter landing area angle compared to the angle of the takeoff on jump 3 should in fact theoretically cause high values of EFH (Hubbard et al., 2009, p. 178; Levy et al., 2015, p. 230; McNeil et al., 2012, p. 6; Swedberg & Hubbard, 2012, p. 122). The lower EFH on jump 3 could be explained by a lower takeoff velocity on jump 3 compared to jump 2. The only difference in takeoff velocity, however, was between jump 2 and 3 for snowboarders. Still, skiers also showed a lower EFH on jump 3. A third explanation of the relatively low EFH on jump 3 may be that the athlete actively adjusted the velocity vector with a negative pop to make the flight trajectory more similar to the landing angle. This is just speculations since there are no physical data on “pop” for this thesis. Lastly, EFH is sensitive to heights (Hubbard et al., 2009, p. 178), and another possible explanation of why the EFH is low, might be because jump 3 can be considered a Step-up jump, with the knuckle and landing area higher compared to jump 1 and 2 (Figure 3). Consequently, the actual fall height might not be very high.

Regardless of the fact that jump 3 has low EFH, the jump shows the highest percentage of bad landings within the three jumps. The observed landing stability might be explained by the fact that the jump 3 is a Step-up jump. Limited perception over the landing area might reduce the athlete’s control when leaving the takeoff. This might reduce the experience of safety and control and cause insecurity, interrupting the athlete’s flow (Hanton & Connaughton, 2002, p. 87). Thus, a maneuver can be more difficult to plan and implement on such a jump, causing under- or over-rotations if the landing area approached faster than expected. It is important to mention that the athletes were familiar with the jumps through training runs, and they are probably used to different shapes of jumps from elite level competitions. Furthermore, the angle of the takeoff was steeper for jump 3 compared to jump 1 and 2 (Figure 3), which to a larger extent may lead the athlete into an unintended inverted body posture (McNeil, 2012a, p. 1), causing instabilities already when the athlete is airborne. It is an important aspect that should be included in further research.

Earlier research has linked EFH to injury risk (Hubbard et al., 2009, p. 178; Levy et al., 2015, p. 230; McNeil et al., 2012, p. 6; Swedberg & Hubbard, 2012, p. 122), and therefore EFH is considered a factor that is contributing to the injury risk in this thesis. For both skiers and snowboarders, jump 2 seem to induce fewer unbalanced landings (Table 5), despite the highest EFH values (Figure 5). The high values of EFH and low percentage of bad landings on jump 2, together with the low values of EFH and high percentage of bad landing on jump 3 is contradictory to the hypothesis that increased EFH increases the risk of bad landings. It might be thought on these low values of EFH, that a higher EFH not necessarily increased the chance of injury risk before the athlete already is unbalanced due to other factors. It can be thought that for example average angular velocity moderates the effect EFH has on landing stability. Interaction effects were investigated, and no significant effect existed. Landing stability in respect to EFH has not been looked at earlier, which removes the possibility to compare the findings with previous research. In fact, there are no evidence of EFH causing instabilities, it is based on assumptions. However, through the work of McNeil and McNeil (2009) and Hubbard et al. (2009), it is reasonable to assume that increased EFH in fact increases risks of injury. It is further possible that EFH affect landing stability above a certain value of EFH. One can see in Figure 5 that mean EFH was low in all three Seiser Alm jumps, relative to the guidelines of maximum EFH from USTPC (McNeil et al., 2012, p. 8), and probably not challenging the athletes landing skills as much as in other types of jumps, such as a Step-down jump. This might come of good engineering abilities within the crew that constructed these jumps (F-Tech, Sterzing, Italy). Future research should look at different jumps from different competitions to ensure a wider specter of EFH values.

These assessment of the three jumps in Seiser Alm might imply that it is possible to build jumps that ensure low EFH and safety while not jeopardizing the exhilaration of the athletes, since bigger jumps might not necessarily mean a higher injury risk. Jump 2 has bigger dimensions (Figure 3), and the athletes show longer horizontal distance on their flight trajectory (Table 6). This is in agreement with Hubbard et al. (2009), who states that the shape of the landing surface can reduce EFH. This is an important finding for the development of the sport, even if this is based on three jumps with low EFH. It can however be a base for further research, exploring larger jumps and jumps with higher EFH than what we have assessed in this study.

Rider behavior

Male athletes seemed to do more advanced maneuvers compared to female athletes, which particularly can be seen through the higher ω_{avg} and percentage of multiaxial maneuvers with male athletes (Table 7). An explanation for this, can among others be a higher muscle-to-mass ratio with male athletes (Janssen et al., 2000, p. 83; Schorr et al., 2018, p. 3), that allows them a better pop at the takeoff and provide more power in rotations around their own axis. It can also be explained by psychological factors that might affect what the athlete can do while airborne, such as a higher search for thrills and sensations among male athletes (Breivik et al., 2017, p. 268; Cross et al., 2013, p. 2). The observed difference was rather big however, indicating that it might derive from cultural aspects rather than physiological factors. Higher competition among male athletes might lead to more training hours to qualify for elite level competitions.

Skiers seemed to perform more advanced maneuvers compared to snowboarders. The observed airtime was also larger for skiers compared to snowboarders, as well as for male athletes compared to female athletes. This supports the fact that increased complexity in maneuvers is allowed for with increased airtime. It also emphasizes the validity of the performance criteria amplitude. Male skiers choose multiaxial maneuvers most of the time (Table 7), probably to get higher scores, due to increased difficulty compared to monoaxial maneuvers. For male snowboarders, it was common to do both monoaxial maneuvers and multiaxial (Table 7). This may indicate that doing multiaxial and monoaxial maneuvers is somehow similar in complexity for snowboarders. As mentioned earlier, comparing freeski and snowboard in complexity of maneuvers might be irrelevant due to fundamental differences in how athletes are attached to the equipment and the equipment's properties that lead to differences in range of motion.

Landing switch was more common for male compared to female athletes (Table 8). This strengthens that switch landings might be more complex and induce a higher risk of injury compared to landing normal, assuming that male athletes do more complex maneuvers compared to female athletes. This is supported by the percentage of switch landings within skiers which was higher in the finals compared to qualifications (Table 11). For snowboarders however, switch landings seem to account for a smaller percentage of the landings in finals compared to qualifications. This supports the theory that switch landing for skiers are more risky, due to limited perception and biomechanical differences from landing normal (Löfquist & Björklund, 2020, p. 1569). Landing switch for snowboarders, however, implies that they have to manage the same technique with both legs in front, which might be unproblematic for elite athletes.

Frontside rotations for snowboarders occur more often in finals, which can indicate that frontside rotations are more advanced compared to backside rotations. In a frontside rotation, one lands with limited perception over the landing area, because the rotation direction is towards the back. Furthermore, when landing, the frontside rotation is stopped by friction on the heel edge of the board, while it might be preferred to land on the toe edge of the board, to easier control posture and balance. However, Kurpiers et al.

(2017, p. 2459) saw that backside rotation more often led to falling compared to frontside rotations, which is contradictory to the theory above. Rotational direction needs further investigations to see how that impact landing stability.

In all arguments concerning rider behavior, there is an assumption that more complex maneuvers lead to both a higher score during competition, but also a higher chance to suffer an injury due to increased risk taking (Breivik et al., 2017, p. 271). Because ranking and points could not be included in this thesis, since points are given based on the total performance of the run, and not given individually for each jump, performance variables can just be assumed. It would be interesting for further research to include such a variable to be able to connect certain variables and risk taking to points.

Competition situational factors

There was a difference in unbalanced landings between qualifications and finals for skiers (Table 9). Apart from that, no differences were observed in landing quality for skiers and snowboarders. The observed difference between qualifications and training in landing quality for snowboarders can be explained by the fact that more risks are taken in competition situations. This is visual in Table 10, with the fact that ω_{avg}, airtime and axial motions advances between all heats for snowboarders. The fact that airtime increases, may be a result of more “pop” with more skilled athletes. This has not been investigated in this thesis, but may be interesting to look at in further research. Of course, the more complex maneuvers of the finals may be because less skilled participants are excluded. Skiers however reproduce their low percentage of falls and bad landing stability in both finals, qualifications, and trainings. What is expected to be seen is that the best athletes might save their best maneuvers and highest risks to the finals, while other athletes perform their best during qualification to ensure a spot in the final. Probably a mix of these factors cause no significant differences in landing quality between training, qualification, and finals.

Potential injury risk factors

For skiers, EFH, axial motions and sex were significant predictors for landing stability (Table 12). Skiers showed the highest probabilities of bad landing stability when doing a monoaxial maneuver with increased ω_{avg} and increased EFH (Appendix 2, section 1.2). In addition, skiers showed a significant interaction effect between ω_{avg} and axial motions, and ω_{avg} and sex, which means that the affect one of these variables has on landing stability, is regulated by the other variable. These interaction effects seemed to remove the main effect of ω_{avg}. For snowboarders, there was a significant main effect of EFH, ω_{avg} and switch orientation during landing (Table 13), which means that the highest probabilities of bad landings came with an increase in ω_{avg}, increased EFH and with switch landing orientation. For snowboarders, axial motions were not a significant predictor of landing stability. Hence, all hypotheses that concerned main effects could be confirmed, except from h_3 which involved axial motions.

The models produced in this thesis might not be sufficient to explain the whole variance of landing stability in the dataset. There are factors that might cause instability that happen before the athlete is airborne which are not considered in this thesis. Furthermore, inconsistencies in the snow surface could not be controlled for. However, the probabilities given is an indication of how the variables that are investigated affect landing stability. All probabilities of bad landing stability in this section are available in Appendix 2, which contain matrixes that consider different values of the variables from the logistic regression for skiers and snowboarders, and calculate the total probability of a bad landing outcome based on these values.

EFH as a predictor of landing stability outcomes

There is a general trend for all groups that the probability of a bad landing in fact increases with an increase in EFH (Appendix 2). This confirms h_1 and is an important finding that agrees with previous research that claims that EFH increases injury risk (McNeil et al., 2012, p. 9; Moore et al., 2021, p. 6; Swedberg & Hubbard, 2012, p. 122). The relationship between EFH and a surrogate measure of injury risk such as stability has not been empirically investigated earlier, which means that this is new independent knowledge that supports the hypothesis that EFH might increase the injury risk. The EFH values of the jumps were rather low in this project (Hubbard et al., 2009, p. 179; McNeil & McNeil, 2009, p. 162), and future research should include different jumps to get a wider specter of EFH values.

Angular velocity and axial motions predictors of landing stability

ω_{avg} was a significant predictor of bad landing stability for snowboarders. For skiers, ω_{avg} showed no main effect, but was significant in interaction with axial motions, and with sex. Hence, the probability of bad landing stability increased with an increase in ω_{avg} for all groups, except for female skiers in multiaxial maneuvers. The fact that probability of bad landing stability mainly increases with an increase in ω_{avg}, agrees with the assumption that ω_{avg} determines complexity of a maneuver. However, for female skiers the probability of bad landing stability decreased with increased ω_{avg} when performing a maneuver with multiple axes (section 1.1.2 and 1.1.4 in appendix 2). For male skiers, even if the probability of bad landing stability increased with increased ω_{avg} when performing a multiaxial maneuver, on ω_{avg} faster than 519 °/s, the probability of bad landing stability was smaller if doing a multiaxial maneuver (Appendix 2, section 1.2.2), compared to doing a monoaxial maneuver on the same ω_{avg} (Appendix 2, section 1.2.1). This interferes with the idea that multiaxial maneuvers are more complex and induce injury risks. Male skiers do multiaxial maneuvers over 90 percent of the runs (Table 7), with no difference between finals, qualifications, and trainings (Table 10). For female skiers, the distribution between monoaxial and multiaxial maneuvers were more even. Because male elite skiers prefer multiaxial maneuvers, it is still reasonable to believe that multiaxial maneuvers are more complex and leads to higher scores compared to monoaxial maneuvers, only without the assumed appurtenant injury risk.

It can seem like monoaxial maneuvers are as complex as multiaxial maneuvers for snowboarders. This theory is supported by the difference between performing monoaxial and multiaxial maneuvers for snowboarders in Table 7. Axial motions were not a significant predicator of bad landing stability for snowboarders, and results concerning this variable should therefore be carefully interpreted. By seeing trends of probabilities of bad landing stability for snowboarders due to multiaxial maneuvers (section 2 in Appendix 2), it seems like multiaxial maneuvers show the highest probabilities of bad landing stability during lower ω_{avg}, while monoaxial maneuvers showed higher probabilities of bad landing stability during higher ω_{avg}.

The ω_{avg} in monoaxial maneuvers is occurring around one axis, often the vertical axis, and not distributed across several axes as in multiaxial maneuvers. When counting rotations, rotations around different axes were not distinguished. Therefore, with the calculated ω_{avg} in this thesis, an ω_{avg} of for example 621 °/s for male snowboarders in a 1260 monoaxial rotation would actually rotate the athlete around a vertical axis with an ω_{avg} of 621 °/s, while in a 1260 multiaxial rotation with the same ω_{avg} of 621 °/s, the component of the ω_{avg} that would rotate the athlete around the vertical axis would be smaller because the rotation direction has several axes. This can be a reason for why snowboarders might have an insignificant effect of axial motions, and skiers show lower probabilities of bad landing stability when performing multiaxial maneuvers compared to monoaxial maneuvers. According to the impulse-momentum principle, the change of momentum of an object, will be equal to the impulse that is applied to the object. In this case, that is written as

$$\tau * t = m \, \Delta \, \omega$$

where τ is the torque of the forces between the equipment and the snow surface, t is the time it takes from the equipment touches the ground with an ω_{avg} (ω_0), until the ω_{avg} is stopped (ω_{end}), m is the mass of the object and $\Delta\omega$ is the change of ω_{avg} from V_0 to $V_{end.}$ When ω_{avg} is higher around the vertical axis as in the above example of a 1260 rotation, the $\Delta\omega$ is higher, which requires a larger impulse to stop the rotation. The torque that stops the rotation of the board, consist of friction forces between the snow and the board edge that is engaged with the snow, and the distances between the points on the board edge that are in contact with the snow and the axis of rotation. Assuming that t doesn't change much since the board needs to be stopped from rotating quickly in order to establish balance, and that that the lever arm of the friction forces is the same, the friction forces must be higher to create a sufficient τ to stop the rotation. The athlete has to adjust the orientation of the equipment in a mediolateral plane, for the edges to meet the snow surface and thereby create higher friction forces. Adequate loading and edging of the equipment to stop the angular momentum might be challenging since a relatively large torque might need to be generated over a limited period of time. This might set higher demands on the athletes coordinative and physical skills. Due to moment of inertia, the impulse will be transferred to the body of the athlete, which puts demands to the athlete's motor control to maintain balance. During the braking of the ω_{avg} on the equipment, the body of the athlete will continue to rotate unless muscular work stops the rotation. Assuming that the ω_{avg} of the body of the athlete is as big as the ω_{avg} of the board while airborne, the torque produced by muscular work to stop the rotation must be nearly equal to τ. In contrast, stopping rotations around the horizontal axis might require less effort, because the rotation happens in the same plane as the velocity vector the athlete has after landing. The athlete only has to "drop" down before landing, while the longitudinal torsion stiffness of the equipment might help to stop the rotation. One can therefore argument that a higher muscular work and demand to motor control is required to stop the rotation around a vertical axis in a monoaxial maneuver compared to a multiaxial maneuver. This can cause a higher probability for bad landings for higher ω_{avg} in monoaxial maneuvers, compared to multiaxial maneuvers. This applies to both skiers and snowboarders, but it can be speculated that skiers have more possibilities and capacities to generate and resist the torque that is generated to stop the angular momentum. They land with an orientation forward and can manipulate the width of the pressure area from the skis, to resist the moment of inertia. Snowboarders on the other hand, land sideways with the feet attached to the board, and with only one edge between equipment and snow to generate the torque. Stability and balance might therefore be harder to obtain and maintain for snowboarders compared to skiers.

The unexpected results especially for female skiers, can be caused by methodological weaknesses, undiscovered interaction effects or coincidences. The range of variance in ω_{avg} for monoaxial and multiaxial maneuvers may also affect the outcome. Regarding the fact that training jumps were included in the analysis, and that jumps where the athlete did not perform a maneuver were categorized as monoaxial jumps, the percentage of monoaxial maneuvers with rotation in one axis get small for especially male skiers. Furthermore, multiaxial maneuvers did rarely occur on rotations under 540 degrees. For female skiers, this would result in a mean ω_{avg} of 284 °/s, which is in the middle of the matrixes for female skiers (Section 1.1 in Appendix 2). Since the matrixes are based on the maximum values of ω_{avg} of each group, the datapoints in which there are actual data for multiaxial maneuvers gets limited. The probabilities for bad landing stability on the rows of the matrix with ω_{avg} that don't contain empiric data, might therefore be inaccurate. This can be an explanation of the inverted trend of a decreased probability of bad landing stability, with an increase in ω_{avg} in multiaxial maneuvers for female skiers. This might be considered a methodological weakness. A rotation of 540 °/s corresponds to a mean ω_{avg} of 260 °/s for male skiers (see matrixes in section 1.2 in appendix 2), and they have a maximum ω_{avg} that is higher compared to female skiers, which implies that the range of ω_{avg} that was performed in a multiaxial maneuver were larger for male athletes. Therefore, the calculation of beta coefficients might be more accurate compared to female skiers.

This is the first study to look at ω_{avg} and axial motions in relation to landing stability. To investigate this relationship further, an experimental design to test the different ω_{avg} on both mono- and multiaxial maneuvers could be interesting. Of course, within ethical limits with maneuvers and ω_{avg} the athletes are comfortable with. Axial motions are an aspect that can be interesting to look at in further research, but for this project, it looks like the presence of multiaxial maneuvers actually decreases the probability of bad landing stability compared to monoaxial maneuvers for skiers. This interferes with the assumption that multiaxial maneuvers were more complex and induced higher risks. For snowboarders the probabilities of bad landings remain the same regardless of if the maneuver were monoaxial or multiaxial.

Switch landing as a predictor of landing stability outcomes

For skiers, landing switch had no significant effect in the prediction of landing stability. This rejects the theory that limited view decreases landing stability for skiers. For elite athletes this effect might be neglected due to very high-level athletes. The result might be different for recreational athletes. For snowboarders however, switch landings were significant predictors of bad landing outcomes, which can be explained by reduced motor control and degrees of freedom compared to landing with the preferred front foot in front. To the best of our knowledge, no one else has looked at landing stability in relation to switch landing earlier.

Interaction effect between ω_{avg} and sex

If a male skier performed a certain maneuver, the risk of injury seemed to be reduced compared to if a female skier did the same maneuver. This can be explained by a higher skill level, but also a higher muscle mass which enhances the ability to withstand impacts upon landing (Janssen et al., 2000, p. 83; Schorr et al., 2018, p. 3). Contradictory to that was the significant interaction effect between ω_{avg} and sex, where the probabilities of bad landing stability increased with an increase in ω_{avg} if the athlete was of male sex. This can be because male athletes are typically more thrill-seeking and might try out maneuvers that are beyond their level of skills (Breivik et al., 2017, p. 268; Cross et al., 2013, p. 2). These maneuvers may include high values of ω_{avg}, while female athletes choose safer options and therefore perform maneuvers with ω_{avg} they are comfortable with.

Methodical considerations and limitations

This investigation is a part of an ongoing project that spans over several years, and the data is from a competition in 2018. Because this is a growing sport, and because the disciplines recently have been included in the Olympics, the maneuvers might develop rapidly. The observed rider variabilities might be out of date, and new data might be collected to be able to predict landing stability for today's rider behavioral factors.

Firstly, there were differences in weather conditions between the competition days. Also, fog led to missing data on one of the competition days. These factors may impact the maneuvers and performance of the athletes on these days, which is not fully controlled for in this thesis, and should be considered in further research. Wind conditions were reported however, and because the wind throughout the data collection were somewhat constant, this might not affect the variance in landing stability in this investigation since conditions were similar each day. How wind condition affects what maneuvers the athlete choses to perform cannot be controlled for, and may be considered in future research.

Rider behavioral factors are based on subjective observations, conducted by three persons analyzing each their set of videos. Different persons might have different interpretations of the variables. Even if there were definitions and rules of how to evaluate the different variables, this can be a source of error, and weaken the intra reliability of the assessment. In earlier qualitative assessments, the same set of videos have been conducted by several analysists, and at least three had to agree for a variable to be valid (Bakken et al., 2011, p. 1316; Bere et al., 2011, p. 1423). This group only analyzed 20 videos, while this investigation included 1321 videos. Kurpiers et al. (2017, p. 2458), also had a large data set. They did reliability tests to look at inter- and intra-observer reliability, by randomly choosing 20 videos of their dataset, that three analysists analyzed individually. One person also analyzed the videos three times with one wash out week in between. This was not done for this investigation but should be included in further research to ensure a common understanding and interpretation of the variables.

Since Computer Vision based annotations of CoM was less successful than desired, the athletes' CoM were manually annotated, which might result in a less accurate 3D-model of the athletes' trajectories. The annotations were done by two persons that annotated each their set of videos and coordinated where to place CoM. Through computer vision, CoM where calculated based on position of the limbs, while during manual annotation, CoM were placed on a predicted CoM-position based on the position of the hip and limbs of the athlete. Indistinct images made it hard to distinguish the athlete from the background, and the limbs and hips from the body of the athlete. This could in some cases lead to misplacing of CoM. Other times, frames were left out of the manual annotation to avoid misplacement of CoM. Due to this, many runs were lost in data processing, resulting in valid 3D-trajectories with possibilities to calculate physical data as EFH for only 654 of 1321 videos. Yet, the dataset is relatively big compared to what has been done before, and with EFH together with rider behavior, the dataset is rich compared to what has been presented elsewhere in the literature.

In this project the analysis is limited to look at potential mechanisms that cause instability after the athlete leaves the takeoff. Everything in prior to that is not inspected. Curvature of the takeoff is an example. Snowboarders and skiers might respond differently to different curvatures, regarding the fact that skiers have a narrower pressure area on the equipment compared to snowboarder who will distribute pressure on a wider part of the longitudinal axis on the board. Mistakes during takeoff might cause instability for the athlete already while being airborne. For further research, loss of control during airborne phase may be a variable of interest. It was initially meant to be included in this investigation, but we could not find any good definition and operationalization of "bad air balance". It was hard to distinguish "bad air balance" from style and techniques the athlete did to slow down rotation. In fact, Kurpiers et al. (2017, p. 2459) also wanted to include this variable in their analysis, but it was excluded due to insufficient reliability.

It might not only be the number of rotations or ω_{avg} that affect landing stability for athletes, but also the degree that the athlete manages to land with longitudinal axis of the equipment oriented in the same direction as the athlete's velocity vector, including normal and switch landings. Over- or under-rotations may cause the athlete to land with the equipment oriented in a direction that deviates from the velocity vector of the athlete, which can throw the athlete out of control once it gets in contact with the ground. Hence, it is a limitation that over- and under-rotations are not reported in this investigation, and it should be included in future research.

Practical implications

To the best of our knowledge, this is the first project to look t many of the aspects that are investigated in this thesis. This new knowledge is important for practitioners and the academic community at the same time.

EFH has not been empirically tested earlier, with actual measurements of velocity components during landing. By relating the results in this thesis with landing stability, there is actual data that can relate landing impact to potential injury risk through surrogate measures. Even if earlier research has proposed this relationship through theory, finding proof of this through empiric data is very important for further investigations and theory.

This investigation indicates that the construction of bigger jumps does not imply higher EFH values during landing. Jump 2 has larger jump dimensions, but a lower EFH. This is an important finding, considering that athletes are judged based on variety, difficulty, execution, progression, and amplitude, which imply that they have to challenge some boundaries when performing advanced maneuvers during large flights. Following the development of the sport, where athletes are continuing to do more complex maneuvers, this might require higher airtime which can be provided by bigger jumps. Thusly, this project can show with empiric data, that bigger jumps can be built to maintain the athletes’ exhilaration, without increasing injury risks.

Rider behavioral factors do affect the probability of bad landing outcomes. By looking at the first matrix of female skiers as an example (Appendix 2, section 1.1.1), one can see that female skiers who perform monoaxial maneuvers with a normal landing orientation and an EFH of 0,5 m, have a 1 % chance to suffer a bad landing with an ω_{avg} of 0 °/s, while it is 11 % chance for a bad landing to occur with an ω_{avg} of 568 °/s. In the same example as above (Appendix 2, section 1.1.1), but with an EFH of 1,5 m., there would be a 24 % chance of a bad landing to occur with an ω_{avg} of 0 °/s, and a 75 % chance of a bad landing to happen with an ω_{avg} of 568 °/s. This new type of very practical information will allow scientists and practitioners to understand the implications of rider behavior and course constructions and puts emphasis on the demand to construct jumps with a low EFH.

Conclusion

To conclude, both rider behavior and EFH seem to increase the probability of bad landing stability for skiers and snowboarders, which emphasizes the need to construct jumps with low EFH to reduce injury risks. Increased ω_{avg}, increased EFH and switch rider orientation during landing showed the highest probabilities of bad landing stability for snowboarders, while the highest probabilities of bad landing stability for skiers came with increased ω_{avg} in monoaxial maneuvers, and increased EFH. Snowboarders seemed to have more unstable landings compared to skiers, which can be caused by the fact that skiers have a higher capacity to compensate for instabilities. Furthermore, this project indicates that jumps with larger jump dimensions did not imply a higher injury risk, which emphasizes that one can construct large jumps that maintain the athletes' exhilaration while keeping injury risks low. Lastly, these findings relate EFH to surrogate measure of injury risks with empiric data, and supports that landing stability, and hence injury risk gets challenged with an increase in landing impact. This is important new type of information for practitioners and scientists.

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List of tables

List of Figures

Appendix 1 – variables from qualitative assessment

Explanations of the variables observed from video analysis. SB=snowboard. If the variable name includes SB, the variable is for snowboarders only. If the variable name includes SKI, the variable is for freeski only. (n): the number of data points in the project. * = variables with two columns, in which one is the categorical variable, while the other is the same variable but coded to 0 or 1. The code is shown in parentheses after the category.

Cell	**Variable**	**Explanation**
A	Cell identifier	Each datapoint have a number, ascending from 1 to (n). Purpose of this column, is to keep order on the original order.
B	Location	Seiser Alm, Mönchengladbach, Beijing or Modena.
C	Discipline	Big Air or Slopestyle
D & E*	Equipment	Freeski (0), SB (1).
F & G	Video number	Two video files, from cameras filming the same run from different angles.
H	Bib	Number on the Bib of the athlete
I & J	Sex	Male (0), female (1). Uknown sex (NaN).
K	Heat	Explaining if it was qualification, finals or training.
L	Run number	1 for the athlete’s first run in the current competition and 2 and 3 for the athlete’s second and third run of the competition.

M	Jump number	1 for all Big Air events, and 1, 2, 3 for the three consecutive jumps in Slopestyle events.
N & O	Stance (SB)	The dominant front foot of the athlete. This is public data from the start lists of the competitions. Goofy/regular and right/left.
P & Q	Athlete orientation	The foot the rider has in front during the takeoff (left/right). Cell Q defines normal, or switch based on Stance, and front foot during takeoff.
R	Rotational direction (SB)	Backside or frontside Rotations. If backside: the back faces the downhill after 90 degrees. If frontside: the face faces the downhill after 90 degrees.
S	Athlete orientation (SKI)	Explains the orientation of the athlete on the takeoff. If the Normal: The athlete is facing the jump. Switch: If the athlete is facing away from the jump.
T	Trick	In this thesis, the maneuver is simplified and defined by the direction of rotations. All maneuvers can be done single, double, or triple, depending on the number of flips in the maneuver. For SKI and SB: Flip: One rotation around a horizontal axis. Spin: One rotation around a vertical axis. Backflip: One rotation counterclockwise around a horizontal axis. Frontflip: One clockwise rotation around a horizontal axis. Cork: a maneuver that combines spins and counterclockwise flips. The maneuver is off axis, implying that the athlete never is fully inverted.

		For freeski: Bio: an off-axis maneuver that combines spins and clockwise flips. Misty: A maneuver that combines spins and clockwise flips. A misty contains a truer flip, compared to a Bio, implying that the athlete can be fully inverted. Rodeo: A maneuver that combines spins and counterclockwise flips. The flip in a Rodeo is truer than in a Cork, implying that the athlete can be fully inverted. For SB: Underflip: A flip where the athlete does a 90 degrees frontside rotation on the lip of the takeoff, followed by a counterclockwise flip. Frontside Rodeo: Off axis spin, where the rotation happens from the toe edge, even if it is frontside. Boxed as polyaxial, but do not actually imply any flips. Backside rodeo: Off axis spin, where the rotation happens from the heel edge, even if it is backside. Can look like a counterclockwise flip, with an additional 180 spin.
U & V*	Axis	Monoaxial (0) and Multiaxial (1)
W	Rotations	How many degrees the athletes are rotating. Simplified by counting one full round as 360 degrees, using for example when the athlete faces the hill as the reference point.
X	Angular Velocity	Rotation / Airtime
Y	Time takeoff	The time of the last frame when the athlete touches the take ff with any part of the ski/snowboard.
Z	Time landing	The time of the first frame when the athlete touches the landing with any part of the ski/snowboard

AA & AB	Airtime	Time landing – time takeoff. Cell AB = airtime + 0,04 seconds
AC & AD	Landing orientation	Landing regular or normal. AAC = SB, AAD = SKI
AE	Landing events (good, Slight unbalance Touch Fall)	A qualitative assessment of the balance of the rider in the landing. If good: the rider performs the landing with apparent stability and control. If slight unbalance: the rider performs the landing with apparent instability but stays in control. If touch: the rider performs the landing with instability and little control and touches the ground with one or two hands to remain an upstanding position. If fall: the rider lacks control and stability while landing, ending in fall.
AF	Fall	If balance landing were “good”, “slight unbalanced” or “Touch”, this column was coded to 0. Fall = 1.
AG + AH*	Landing stability	A qualitative assessment of the stability of the athlete in the landing, based on values from “balance landing”. If good (0): the landing was categorized as either good or slight unbalanced. If bad (1): the landing was categorized as either touch or fall.
AI + AJ	Landing Balance	A qualitative assessment of the balance of the athlete in the landing, based on values from “balance landing”. If balanced (0): the landing was categorized as good. If Unbalanced: the landing was categorized as either slight unbalanced, touch or fall. Coded to 1.
AK	EFH	Values of EFH from the 3D-trajectory.

Appendix 2 – Probability of bad landing stability

These matrixes are based on beta values as can be seen in Table 12 for skiers and 13 for snowboarders in the article. Probabilities (P) are calculated through the equation:

$$P = e \wedge E(Y) / 1 + e \wedge E(Y)$$

e is Euler's constant value, and E(Y) is the total of the values of the variables in the equation times their beta coefficient. The matrixes are divided into subgroups, and there are four matrixes for each group. The matrixes have EFH values on the x axis and Angular velocity values on the y axis. Maximum values are based on the maximum value of the variable for each group. By using the equation above, extrapolation is possible if wanting to look at higher values. The EFH values are chosen as standard intervals. Angular velocity values represent the mean ω_{avg} of 180 degrees turn, 360 degrees turn, 540 degrees turn etc. for each group, and are calculated as 180°/mean airtime of group. The four different matrixes per group represent different situations with the presence and absence of the binary variables, defined above each matrix. If wanting to see the probability of a male skier who does a multiaxial maneuver, lands regular, having an EFH of 1 meter, and an ω_{avg} of 346 **°/s,** one has to find the intersection of the x and y axis on the matrix in section 1.2.2. The probability would be 11 percent for a bad landing.

1. Freeski

1.1 Female skiers

1.1.1 Probability of a bad landing if a female skier does a monoaxial maneuver and lands normal.

		EFH				
		0 m	**0,5 m**	**1 m**	**1,5 m**	**2 m**
ω_{avg} (°/s)	**0 °/s**	0,00	0,01	0,06	0,24	0,60
	95 °/s	0,00	0,02	0,09	0,31	0,69
	189 °/s	0,01	0,03	0,12	0,40	0,76
	284 °/s	0,01	0,04	0,17	0,49	0,83
	379 °/s	0,01	0,06	0,23	0,59	0,87
	474 °/s	0,02	0,08	0,30	0,67	0,91
	568 °/s	0,03	0,11	0,38	0,75	0,94

1.1.2 Probability of a bad landing if a female skier does a multiaxial maneuver and lands normal.

		EFH				
		0 m	**0,5 m**	**1 m**	**1,5 m**	**2 m**
ω_{avg} (°/s)	**0 °/s**	0,33	0,71	0,92	0,98	1,00
	95 °/s	0,20	0,56	0,86	0,97	0,99
	189 °/s	0,12	0,39	0,76	0,94	0,99
	284 °/s	0,06	0,25	0,62	0,89	0,97
	379 °/s	0,03	0,15	0,46	0,80	0,95
	474 °/s	0,02	0,08	0,30	0,68	0,91
	568 °/s	0,01	0,04	0,18	0,52	0,84

1.1.3 Probability of a bad landing if a female skier does a monoaxial maneuver and lands switch.

ω_{avg} (°/s)	***EFH***				
	0 m	**0,5 m**	**1 m**	**1,5 m**	**2 m**
0 °/s	0,00	0,01	0,06	0,24	0,61
95 °/s	0,00	0,02	0,09	0,32	0,70
189 °/s	0,01	0,03	0,12	0,41	0,77
284 °/s	0,01	0,04	0,17	0,50	0,83
379 °/s	0,01	0,06	0,23	0,60	0,88
474 °/s	0,02	0,08	0,31	0,68	0,91
568 °/s	0,03	0,12	0,39	0,76	0,94

1.1.4 Probability of a bad landing if a female skier does a multiaxial maneuver and lands switch.

ω_{avg} (°/s)	***EFH***				
	0 m	**0,5 m**	**1 m**	**1,5 m**	**2 m**
0 °/s	0,34	0,72	0,93	0,98	1,00
95 °/s	0,21	0,57	0,86	0,97	0,99
189 °/s	0,12	0,40	0,77	0,94	0,99
284 °/s	0,07	0,26	0,63	0,89	0,98
379 °/s	0,04	0,15	0,47	0,81	0,95
474 °/s	0,02	0,08	0,31	0,69	0,91
568 °/s	0,01	0,05	0,19	0,53	0,85

1.2 Male skiers

1.2.1 Probability of a bad landing if a male skier does a monoaxial maneuver and lands normal.

EFH (m)

ω_{avg} (°/s)	**0 m**	**0,5 m**	**1 m**	**1,5 m**	**2 m**
0 °/s	0,00	0,00	0,00	0,00	0,00
87 °/s	0,00	0,00	0,00	0,00	0,01
173 °/s	0,00	0,00	0,00	0,01	0,03
260 °/s	0,00	0,00	0,01	0,03	0,13
346 °/s	0,00	0,01	0,03	0,13	0,43
433 °/s	0,01	0,03	0,14	0,44	0,79
519 °/s	0,03	0,15	0,46	0,80	0,95
606 °/s	0,15	0,47	0,81	0,95	0,99
692 °/s	0,48	0,82	0,96	0,99	1,00
779 °/s	0,83	0,96	0,99	1,00	1,00

1.2.2 Probability of a bad landing if a male skier does a multiaxial maneuver and lands normal.

EFH (m)

ω_{avg} (°/s)	**0 m**	**0,5 m**	**1 m**	**1,5 m**	**2 m**
0 °/s	0,00	0,00	0,01	0,04	0,16
87 °/s	0,00	0,00	0,02	0,07	0,28
173 °/s	0,00	0,01	0,03	0,14	0,43
260 °/s	0,00	0,01	0,06	0,24	0,61
346 °/s	0,01	0,03	0,11	0,39	0,75
433 °/s	0,01	0,05	0,20	0,56	0,86
519 °/s	0,02	0,10	0,34	0,71	0,92
606 °/s	0,04	0,17	0,51	0,83	0,96
692 °/s	0,08	0,30	0,67	0,91	0,98
779 °/s	0,15	0,46	0,80	0,95	0,99

1.2.3 Probability of a bad landing if a male skier does a monoaxial maneuver and lands switch.

EFH (m)

ω_{avg} (°/s)

	0 m	0,5 m	1 m	1,5 m	2 m
0 °/s	0,00	0,00	0,00	0,00	0,00
87 °/s	0,00	0,00	0,00	0,00	0,01
173 °/s	0,00	0,00	0,00	0,01	0,03
260 °/s	0,00	0,00	0,01	0,03	0,13
346 °/s	0,00	0,01	0,03	0,14	0,44
433 °/s	0,01	0,03	0,14	0,45	0,80
519 °/s	0,04	0,15	0,46	0,81	0,95
606 °/s	0,16	0,48	0,82	0,96	0,99
692 °/s	0,49	0,83	0,96	0,99	1,00
779 °/s	0,84	0,96	0,99	1,00	1,00

1.2.4 Probability of a bad landing if a male skier does a multiaxial maneuver and lands switch.

EFH (m)

ω_{avg} (°/s)

	0 m	0,5 m	1 m	1,5 m	2 m
0 °/s	0,00	0,00	0,01	0,04	0,17
87 °/s	0,00	0,00	0,02	0,08	0,29
173 °/s	0,00	0,01	0,03	0,14	0,44
260 °/s	0,00	0,01	0,06	0,25	0,61
346 °/s	0,01	0,03	0,12	0,40	0,76
433 °/s	0,01	0,05	0,21	0,57	0,86
519 °/s	0,02	0,10	0,35	0,72	0,93
606 °/s	0,04	0,18	0,52	0,84	0,96
692 °/s	0,08	0,30	0,68	0,91	0,98
779 °/s	0,15	0,47	0,81	0,95	0,99

2. Snowboard

2.1 Female snowboarders

2.1.1 Probability of a bad landing if a female snowboarder does a monoaxial maneuver and lands normal.

		EFH				
		0 m.	0,5 m.	1 m.	1,5 m.	2 m.
ω_{avg} (°/s)	0 °/s	0,02	0,06	0,16	0,34	0,59
	99 °/s	0,04	0,11	0,25	0,48	0,72
	198 °/s	0,07	0,18	0,38	0,63	0,83
	297 °/s	0,12	0,28	0,53	0,76	0,90
	396 °/s	0,21	0,42	0,67	0,85	0,94

2.1.2 Probability of a bad landing if a female snowboarder does a multiaxial maneuver and lands normal.

		EFH				
		0 m.	0,5 m.	1 m.	1,5 m.	2 m.
ω_{avg} (°/s)	0 °/s	0,05	0,12	0,27	0,51	0,74
	99 °/s	0,07	0,16	0,35	0,60	0,81
	198 °/s	0,09	0,23	0,45	0,69	0,86
	297 °/s	0,13	0,30	0,55	0,77	0,90
	396 °/s	0,19	0,39	0,64	0,83	0,93

2.1.3 Probability of a bad landing if a female snowboarder does a monoaxial maneuver and lands switch.

		EFH				
		0 m.	0,5 m.	1 m.	1,5 m.	2 m.
ω_{avg} (°/s)	0 °/s	0,05	0,12	0,28	0,51	0,75
	99 °/s	0,08	‘0,20	0,41	0,66	0,84
	198 °/s	0,14	0,31	0,56	0,78	0,91
	297 °/s	0,23	0,45	0,69	0,86	0,95
	396 °/s	0,35	0,59	0,80	0,92	0,97

2.1.4 Probability of a bad landing if a female snowboarder does a multiaxial maneuver and lands switch.

		EFH				
		0 m.	0,5 m.	1 m.	1,5 m.	2 m.
ω_{avg} (°/s)	0 °/s	0,09	0,21	0,43	0,68	0,85
	99 °/s	0,13	0,29	0,53	0,76	0,90
	198 °/s	0,18	0,37	0,62	0,82	0,93
	297 °/s	0,24	0,47	0,71	0,87	0,95
	396 °/s	0,32	0,57	0,78	0,91	0,97

2.2 Male snowboarders

2.2.1 Probability of a bad landing if a male snowboarder does a monoaxial maneuver and lands normal.

EFH (m)

ω_{avg} (°/s)	0 m	0,5 m	1 m	1,5 m	2 m
0 °/s	0,01	0,02	0,06	0,15	0,33
89 °/s	0,01	0,04	0,10	0,23	0,45
177 °/s	0,02	0,06	0,15	0,33	0,58
266 °/s	0,04	0,10	0,23	0,46	0,70
355 °/s	0,06	0,16	0,34	0,59	0,80
443 °/s	0,10	0,24	0,47	0,71	0,87
532 °/s	0,16	0,35	0,60	0,81	0,92
621 °/s	0,25	0,48	0,72	0,88	0,95
709 °/s	0,36	0,61	0,81	0,92	0,97

2.2.2 Probability of a bad landing if a male snowboarder does a multiaxial maneuver and lands normal.

EFH (m)

ω_{avg} (°/s)	0 m	0,5 m	1 m	1,5 m	2 m
0 °/s	0,02	0,04	0,11	0,25	0,49
89 °/s	0,02	0,06	0,15	0,33	0,58
177 °/s	0,03	0,08	0,20	0,41	0,66
266 °/s	0,04	0,11	0,26	0,50	0,73
355 °/s	0,06	0,15	0,34	0,58	0,80
443 °/s	0,08	0,21	0,42	0,67	0,85
532 °/s	0,12	0,27	0,51	0,74	0,89
621 °/s	0,16	0,34	0,59	0,80	0,92
709 °/s	0,21	0,43	0,68	0,85	0,94

2.2.3 Probability of a bad landing if a male snowboarder does a monoaxial maneuver and lands switch.

EFH (m)

ω_{avg} (°/s)

	0 m	**0,5 m**	**1 m**	**1,5 m**	**2 m**
0 °/s	0,02	0,04	0,11	0,26	0,50
89 °/s	0,03	0,07	0,18	0,38	0,63
177 °/s	0,05	0,12	0,27	0,51	0,74
266 °/s	0,07	0,18	0,39	0,64	0,83
355 °/s	0,12	0,28	0,52	0,75	0,89
443 °/s	0,19	0,39	0,64	0,83	0,93
532 °/s	0,28	0,53	0,76	0,90	0,96
621 °/s	0,40	0,65	0,84	0,94	0,98
709 °/s	0,54	0,76	0,90	0,96	0,99

2.2.4 Probability of a bad landing if a male snowboarder does a multiaxial maneuver and lands switch.

EFH (m)

ω_{avg} (°/s)

	0 m	**0,5 m**	**1 m**	**1,5 m**	**2 m**
0 °/s	0,03	0,08	0,20	0,41	0,66
89 °/s	0,04	0,11	0,26	0,50	0,73
177 °/s	0,06	0,15	0,34	0,59	0,80
266 °/s	0,09	0,21	0,42	0,67	0,85
355 °/s	0,12	0,27	0,51	0,74	0,89
443 °/s	0,16	0,35	0,60	0,80	0,92
532 °/s	0,21	0,43	0,68	0,85	0,94
621 °/s	0,28	0,52	0,75	0,89	0,96
709 °/s	0,35	0,60	0,81	0,92	0,97