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A biomechanical analysis of how rider behavior and equivalent fall height affect landing stability in World Cup Big air in freeski and snowboard.

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Abstract

Purpose: This study aimed to examine the impact of equivalent fall height (EFH) and rider behavior on landing stability among snowboard and freeski World Cup athletes participating in a Big air event. Furthermore, the study aimed to identify the predictive variables associated with EFH. Landing stability was utilized as a surrogate measure for injury risk. **Methods:** The project included a total of 97 elite athletes. Data collection occurred during the 2016/2017 season at a Big air event held in Mönchengladbach, Germany. A tachymeter-based measurement system (QDaedalus) and computer vision (CV) were employed to track and reconstruct a three-dimensional model of the athlete’s center of mass (COM) trajectories. These trajectories were then used to calculate various physical variables such as EFH, horizontal jump distance, landing angle, drop height, pop, and $V_{Parallel.}$ Additionally, a qualitative assessment of rider behavior and landing stability was conducted, incorporating factors such as average angular velocity (ω_{avg}), axial motions, the direction of rotation, and rider orientation. Logistic regression was performed to investigate the variables that influenced landing stability, while linear regression was utilized to identify variable predictors of EFH. **Results:** Snowboarders exhibited a significantly higher incidence of falls, bad landings ($p<0,001$,) and unbalanced landings ($p<0,05$) in comparison to skiers. This disparity could potentially be attributed to differences in the equipment attachment. Snowboarders have both legs attached to the board in a fixed position, which limits their ability to compensate for imbalances to a lesser extent compared to skiers. None of the variables examined were found to be significant predictors of landing stability in either freeski or snowboarding. Drop height and landing angle emerged as significant EFH predictors in freeski and snowboard ($p<0,001$). **Conclusion:** The elevated EFH values, which were observed to approximately meet the maximally recommended United State Terrain Park Council (USTPC) criterion of 1,5 meters, might diminish the influence of rider behavior factors on landing stability. The step-down jump resulted in remarkable EFH values, emphasizing the significance of designing a landing angle that aligns with the athlete’s flight trajectory. This design consideration is crucial to ensure compliance with USTPC criteria and uphold athlete safety.

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1. Introduction

Snowboard and freeski encompass a variety of disciplines and have become increasingly popular sports over the past decades (Tarazi et al., 1999, p. 177). Big air and Slopestyle have been recently included as disciplines in the Olympic Games (International Olympic Committee, 2021a, 2021b; Martínková & Parry, 2020). According to the literature, both disciplines have been found to pose a high risk of injury (Peng-da Han et al., 2022; Soligard et al., 2019; Soligard et al., 2015). Furthermore, studies indicate that athletes who engage in the terrain park (TP) have a greater likelihood of experiencing severe injuries compared to those on the regular slope (Brooks et al., 2010; Carús & Escorihuela, 2016a; Goulet et al., 2007; Russell et al., 2014). Research has found that skiers and snowboarders participating in the TP have been associated with injury risk of 0,9 and 0,75 per 1000 runs, respectively (Carús & Escorihuela, 2016a; Russell et al., 2013). Additionally, in jumps, the injury risk for skiing and snowboarding has been observed to be 2,9 and 1,8 per 1000 runs, respectively (Carús & Escorihuela, 2016b; Russell et al., 2014). The primary factors contributing to the high risk of injury are the utilization of aerial elements, falls, and the impact upon landing (Brooks et al., 2010; Carús & Escorihuela, 2016a; Moffat et al., 2009; Russell et al., 2013). Consequently, many researchers emphasize the significance of equivalent fall height (EFH) as a crucial factor in assessing the safety of a jump (Hubbard & Swedberg, 2012; McNeil et al., 2012; Moore & Hubbard, 2018)

Limited research has been conducted on the influence of rider behavior on the risk of injury. To the best of our knowledge, only two studies have explored this phenomenon. Kurpiers et al. (2017) examined how rider behavior predicted falling in snowboarders on a table-top jump. However, this study did not include freeski athletes or EFH. Additionally, the analysis was limited to recreational athletes. Linløkken (2022) conducted a similar investigation on elite athletes participating in a Slopestyle event, with jumps categorized as roll-over and step-up. In contrast, this study included freeski athletes and EFH in the analysis. However, these findings cannot be generalized to Big air, which involves longer jumps, increased airtime, more spectacular maneuvers, and a different jump design (step-down) which is associated with a higher risk of injury. Many of the same analyses are performed in this thesis as in the study of Linløkken (2022), to compare the findings and investigate the differences across disciplines.

Consequently, this study is the first of its kind to examine how rider behavior and EFH impact the landing stability of elite athletes participating in a Big air event.

The research findings highlight a significant risk associated with snowboarding and freeski, which can result in long-term detrimental effects on health and withdrawal from sports. Therefore, it is crucial to conduct research to enhance the safety measures for both athletes participating in competitions and recreational athletes using TP. This study aims to contribute to the existing knowledge by examining the impact of rider behavior and EFH on landing stability, while also identifying the parameters that predict EFH. Landing stability was used as a surrogate measure for injury risk. It is important to note that this thesis is part of a bigger ongoing project, with data collection occurring in 2016. The data collection and calculation of physical data are carried out by external parties; hence a brief description of the methodology is provided. The primary focus will be on the analysis and evaluation.

Section 2 explains key terms related to jump components and rider behavior. Section 3 addresses the epidemiology, jump design, and factors contributing to injury risk. The methodology is outlined in Section 4. Section 5 examines the potential injury risk factors associated with rider behavior and EFH, along with the identification of variable predictors of EFH. Section 6 is dedicated to the discussion of the obtained results in comparison to previous research findings. The paper concludes with a summary in Section 9. Additionally, a compilation of figures, tables, and abbreviations is provided at the end. Appendix 1 offers a detailed explanation of the variables included in the data set used for the observational assessment of rider behavior.

1.1 Research question and hypothesis

Research indicates that EFH is the most important factor affecting the safety of a jump and that the leg muscles have an upper limit to absorb energy upon landing (Hubbard, 2009, p. 182; Hubbard & Swedberg, 2012, p. 79; McNeil et al., 2012, p. 6; Minetti et al., 1998, p. 13; Moore et al., 2021, p. 6). Therefore, it is likely that the landing stability will be compromised with an increase in the EFH. Thus, the first hypothesis concerns the impact EFH has on landing stability:

H_1: Landing stability is negatively impacted by EFH for Big air athletes in both freeski and snowboarding.

Different rider behavior factors may enhance the complexity and difficulty of the maneuvers, which may affect the landing stability negatively. According to the research of Linløkken (2022, pp. 66-67), multiaxial maneuvers increased the chance of bad landing stability among freeski. Furthermore, a higher value of ω_{avg} and switch orientation during landing enhanced the chance of bad landing stability among snowboarders. These findings led to the second hypothesis, in addition to four sub-hypotheses:

H_2: Rider behavior has a negative impact on landing stability for Big air athletes in both freeski and snowboarding.

As shown by Linløkken (2022, p. 67), with an increase of ω_{avg} it is probable that landing stability will be adversely impacted. The reason behind this could be that when the value ω_{avg} is high, the athlete would need to counteract a greater momentum upon landing, in addition to having less time to orient themselves in the air, which can result in decreased landing stability. In Big air competitions where athletes perform more complex maneuvers with longer airtimes, it is reasonable to expect similar outcomes as those observed in Slopestyle, which led to the first sub-hypothesis regarding rider behavior:

H_2^1: Angular velocity has a negative impact on landing stability for Big air athletes in both freeski and snowboarding.

When landing switch on freeski, the athlete’s perception of the landing is reduced, which may lead to increased difficulty and negatively influence landing stability. Löfquist and Björklund (2020, p. 1569) did not find a difference in landing force between normal and switch rider orientation during landing in skiers. However, their observations suggest that different techniques are required with different landing orientations, which may affect the landing stability negatively. However, unlike freeski, there is no biomechanical difference between landing switch and normal in snowboard. The athletes included in the study of Löfquist and Björklund (2020) performed maneuvers with minimal complexity. Therefore, the force difference between normal and switch landing orientation upon landing might be affected to a greater extent by the more complex tricks performed in this project. Athletes in both disciplines may exhibit superior edge control while landing in their preferred stance, which could result in reduced landing stability when landing in a switch orientation. This forms the basis of the second sub-hypothesis regarding rider behavior:

H_2^2: Switch rider orientation during landing have a negative impact on landing stability for Big air athletes in both freeski and snowboarding.

It may be more challenging to perform a monoaxial maneuver than a multiaxial maneuver, as the latter enables the athlete to rotate in a way that provides a clearer perspective of the landing while airborne. A multiaxial maneuver could potentially facilitate an athlete to land at an angle that improves the ski-snow interaction and enhance the athlete’s ability to regulate both the magnitude and direction of the reaction force, as described by Reid (2010, p. 21). Consequently, a multiaxial maneuver may simplify edge control, enhance friction generation against the underlying slope, and make it simpler to halt the momentum compared to a monoaxial maneuver with the same angular velocity. The result from Linløkken (2022, p. 76) indicates that monaxial maneuver with high values of ω_{avg} has a higher likelihood of bad landing stability compared to multiaxial maneuvers. Thus, the third sub-hypothesis regarding rider behavior is:

H_2^3: Monoaxial maneuvers have a negative impact on landing stability for Big air athletes in both freeski and snowboarding.

The direction of rotation only applies to snowboarders. When performing a frontside rotation the athlete tends to land towards the heel edge, which may result in less control compared to landing towards the toe edge during a backside rotation. This difference in control may perhaps be explained by the additional degrees of freedom and joint complexity in the toes, which provide better edge control and help to stop the momentum. This theory led to the fourth sub-hypothesis;

H_2[4]**:** Frontside rotation has a negative impact on landing stability for Big air athletes in snowboarding.

Interaction effects

It is possible that there could be an interaction between certain factors when assessing their influence on an outcome. In this case, the axis of rotation may moderate the effect ω_{avg} has on landing stability. The calculation of ω_{avg} in multiaxial rotations has not been separated by different axes due to the complex nature of such calculations. In reality, ω_{avg} would be distributed around several axes in multiaxial maneuvers in contrast to a monoaxial maneuver where ω_{avg} would only be around the longitudinal axis. Rotating around only one axis could have a greater impact on landing stability compared to rotating around several axes with the same ω_{avg}, due to a higher momentum around the longitudinal axis in the monoaxial maneuver. This forms the basis for the third hypothesis;

H_3: Axis of rotation moderates the impact ω_{avg} has on landing stability for Big air athletes in both freeski and snowboarding.

2. Definition of terms

Parameter	**Explanation**
Grab	The athlete touch and hold on to the edge of the equipment while airborne.
Switch	In freeski, the athlete rides downhill in a backward position. In SB, the athlete rides downhill with their dominant foot in the back.
Regular	Left foot is the dominant foot (SB).
Goofy	Right foot is the dominant foot (SB).
Monoaxial	Maneuvers are performed around only one axis.
Multiaxial	Maneuvers are performed around two or several axes.
Frontside rotation	The athlete is rotating from the heel edge and is facing downhill 90 degrees into the rotation.
Backside rotation	The athlete is rotating from the toe edge and is facing uphill 90 degrees into the rotation.
Pop	Muscular work performed at the take-off lip.
Airtime	The duration between take-off and landing during which the athlete is airborne.

Sweet spot	The landing area section where the impact is the smallest.
Approach	The steep section where the athlete develops velocity prior to the take-off.
Transition	The smooth region between the downward approach angle to the upward take-off angle.
Kicker	The total ramp construction of the jump.
Take-off	The above surface of the kicker.
Take-off lip	The last surface of contact before the athlete becomes airborne.
Deck	The flat horizontal section between the take-off lip and the knuckle.
Knuckle	The intersection point between the deck and the landing area.
Bucket	The section where the slope flattens out from the landing towards the run-out.
Butter	The athlete initiates rotation prior to departing from the take-off

3. Theory

3.1 Big air and Slopestyle

Big air and Slopestyle are two different competition formats within snowboard and freeski, where both male and female athletes compete on the same course. Slopestyle consists of rails, jumps, and in some cases halfpipes where the athlete can show creativity by choosing different lines. Big air consists of only one single jump, although it is typically larger than the jumps in Slopestyle. This thesis will assess different aspects related to jumps in Big air, which may also apply to Slopestyle.

3.1.1 Big air

Big air competitions consist of one single jump, where the athletes compete to perform the most spectacular and advanced tricks. The competition is organized in heats for the phases of Qualification and Final with or without Semi-final. The inclusion of the different phases is based on the number of participants in the qualification. Semi-finals are recommended if there are more than 24-30 participants. The competition format may differ between phases and competitions and is determined by the jury based on the time available and the number of participants. There are 12-30 participants in each qualification heat, distributed according to their ranking (FIS Points). The Semi-final consists of 10-24 participants per heat. The final includes 10-12 participants for male athletes and 6-12 participants for female athletes (Fédération Internationale de Ski, 2022, pp. 87-88). The qualification consist of two runs where the best individual score counts. The scoring format in the final can vary between 2 and 3 runs (Fédération Internationale de Ski, 2018, p. 77; 2022, p. 90). The judges give an individual score of maximum 100 points on each performance (Fédération Internationale de Ski, 2022, p. 84).

Fédération Internationale de Ski (2022, p. 74) has established guidelines for the design of Big air jumps. According to these guidelines, the length of the approach (drop-in) should be a minimum of 30 meters, have a minimum inclination of 20°, and have a transition area length of 5-10 meters. The height of the kicker should at least be 2 meters, with a minimum take-off angle of 25°, and a minimum width of 5 meters. For elite athletes, the distance between take-off and landing should be a minimum of 15 meters (10 meters for less advanced). The landing inclination should be a minimum of

28° according to take-off. The length and width of the landing should be a minimum of 20 meters.

3.1.2 Slopestyle

Slopestyle is a course consisting of various features (jumps, boxes, rails, quarter pipes, waves, and ridges), allowing competitors to perform various maneuvers. These features are classified into two groups: aerial features and non-aerial features. Aerial features refer to jumps, half-pipes, and quarter-pipes where the athlete can perform various tricks while airborne. Non-aerial features also known as “jibs”, refer to various designs of rails and boxes that athletes can ride using either a parallel or perpendicular stance to their velocity vector or while executing spins (Carús & Escorihuela, 2016b, p. 86; Moffat et al., 2009, p. 260)

Guidelines established by Fédération Internationale de Ski (2022, pp. 72-73) point out that the Slopestyle course shall be a minimum of 30 meters wide, designed for both male and female athletes, and include a minimum of 2 feature types. The course consists of various sections, each containing multiple features. This allows the athlete to be creative in line selection. The course should allow the participants to spin in multiple directions and not favor one stance over another (regular vs switch). The ideal course should be technically challenging and include a variety of features encouraging diverse combinations. For elite athletes, the length of the course shall be a minimum of 150 meters wide and have a minimum average gradient of 10°. It should also include a minimum of 6 sections, 3 jumps, and 6 judged hits. The participants receive a total score of maximum 100 points for the entire run. Slopestyle events follow the same phases and participant numbers as Big air events (described above).

3.1.3 Judging criteria

When evaluating runs in Slopestyle and Big air competitions, the judges consider the following five criteria equally: Execution, Difficulty, Amplitude, Variety, and Progression. In addition, the overall composition (flow) involving the sequence of tricks, creative use of the course, and the amount of risk-taking are important factors. The subjective aspect of the judges will also influence and may be the determining factor when evaluating tricks that are criteria similar (Fédération Internationale de Ski, 2019, p. 10).

Execution assessment involves take-off, grab, air control, flow, style, and landing. In a well-executed run, the athlete maintains control through the whole trick and shows good stability and fluidity. Proper timing and a clean "pop" at take-off to maximize amplitude are characterized as good execution. Contact with the slope with other body parts than the feet will affect the score negatively. Grabs should be performed throughout most of the trick, enhancing the execution and style. Style is subjective and is often used to separate similar tricks on the same features. Flow is another subjective assessment and is primarily linked to Slopestyle competition and how the athlete put together a run, where the link between the tricks influences the execution and variety (Fédération Internationale de Ski, 2019, pp. 11-12). The difficulty is determined by the complexity of the maneuvers and includes the number of rotations, the direction of rotation, amplitude, grabs performed, and risk-taking. The judges must be able to estimate the difficulty of each trick. Therefore, a discussion of the difficulty of different tricks should take place between judges and competitors before the competition, to provide the same information for all individuals (Fédération Internationale de Ski, 2019, p. 12). High amplitude can accentuate bigger and more spectacular movements and increase the difficulty of the maneuver. Good amplitude is characterized by appropriate speed, clean pop at take-off, high flight trajectory, and landings in the "sweet spot". The trick should match the hangtime and trajectory of the athlete (Fédération Internationale de Ski, 2019, pp. 14-15). Variation is recognized with a complete repertoire of tricks, including different tricks and grabs, multiple directions of movement, multiple directions of rotation at take-off and landing, and rotation around multiple axes. Variety is also characterized by unique line selection and creative use of elements, which especially applies and can be a key factor in Slopestyle competitions (Fédération Internationale de Ski, 2019, pp. 15.-16). The progression criterion is primarily linked to new and unique movements. In addition, creativity, variety, and innovation of common tricks can also increase the score. The judges must have accurate knowledge of the trends and movements in the snowboard and freeski environments, to be able to evaluate the tricks appropriately (Fédération Internationale de Ski, 2019, p. 16).

3.2 Epidemiology

Slopestyle and Big air competitions both involve high-speed, aerial maneuvers that require acrobatic skills and jumps which expose the athlete to large impacts upon landing. According to mapping studies conducted on the Olympics, it has been determined that the risk of injuries is high in both of these disciplines for both minor and severe injuries (Palmer et al., 2021, p. 970; Peng-da Han et al., 2022, p. 461; Ruedl et al., 2012, p. 1032; Soligard et al., 2019, p. 1087; Soligard et al., 2015, p. 443; Steffen et al., 2017, p. 31). Sports such as halfpipe, cross, aerial, Slopestyle, and Big air share a common characteristic that poses a high risk of injury: their inclusion of aerial elements with a substantial fall height, which may lead to instability and falling upon landing (Audet et al., 2021, p. 213; Brooks et al., 2010, p. 120; Carús & Escorihuela, 2016a, p. 417; Moffat et al., 2009, p. 259; Russell et al., 2013, p. 174; Russell et al., 2014, pp. 25-26; Torjussen & Bahr, 2006, p. 232). According to the literature, there is a higher likelihood of individuals experiencing severe injuries who makes use of TP as opposed to injuries sustained on regular slopes (Brooks et al., 2010, p. 120; Goulet et al., 2007, p. 404). Reducing the number of serious injuries is crucial, particularly in young athletes, as it might affect the development of the musculoskeletal structure and potentially lead to long-term damage and withdrawal from sports (Ruedl et al., 2012, p. 1035). Therefore, it is important to develop effective strategies to minimize the injury risk. This section will include a description of the injury characteristics in freeski and snowboarding, including sex, skill level, and TP related injuries.

3.2.1 Ski versus Snowboard

Several papers have reported a strong correlation between the use of TP, particularly aerial elements, and a high occurrence of injuries and their severity (Brooks et al., 2010, p. 120; Carús & Escorihuela, 2016a, p. 417; Carús & Escorihuela, 2016b, p. 88; Goulet et al., 2007, p. 404; Russell et al., 2013, p. 175; Russell et al., 2014, p. 26). According to observations by Carús and Escorihuela (2016a, p. 417), skiers who used the TP had an injury risk of 0.9 per 1000 runs, while Russell et al. (2013, p. 174) observed an injury risk of 0.75 per 1000 runs in snowboarders. Furthermore, the highest risk of ski injury was observed in Big air, with an injury rate of 2.9 and 2.2 per 1000 runs for both overall and severe injuries, respectively (Carús & Escorihuela, 2016b, p. 88). Russell et al. (2014, p. 26) observed a comparable outcome in snowboarding, with half-pipe and jumps having an injury rate of 2.6 and 1.8 per 1000 runs for overall and severe injuries, respectively. Research indicates that snowboarders are more prone to upper extremity injuries, while skiers experience a higher proportion of lower extremity injuries (Brooks et al., 2010, p. 121; Goulet et al., 2007, p. 404; Russell et al., 2013, p. 175). However, Carús and Escorihuela (2016a, p. 417) and Moffat et al. (2009, p. 260) observed a higher likelihood of upper extremity injuries compared to lower extremity injuries in both skiers and snowboarders in TP. It is important to highlight that Moffat et al. (2009, p. 259) did not specify the location of injuries in relation to discipline, but rather presented the overall injury pattern for both freeski and snowboard athletes. Their study reported that 69% of the injured participant in the TP were snowboarders. It is worth considering that previous research has indicated that snowboarders tend to have a higher proportion of upper extremity injuries, which might explain the comparatively higher reported proportion of upper extremity injuries in freeski in their study. Upon conducting a more thorough analysis of Moffat et al. (2009, p. 261), the study revealed that 93% of those who suffered upper extremity injuries were snowboarders, while 75% of the athletes who experienced lower extremity injuries were skiers. These findings align with previous research in the field.

In snowboarding, a greater proportion of knee injuries has been observed in Big air, half pipe, and snowboard cross compared to slalom (Major et al., 2014, p. 20). Furthermore, knee injuries are the most frequently injured body part in both snowboarding and skiing and represent around ~18% and ~26,5% of all injuries, respectively (Flørenes et al., 2010, p. 805; Major et al., 2014, p. 21; Torjussen & Bahr, 2005, p. 375; 2006, p. 232). Tarazi et al. (1999, p. 178), found that snowboarders had four times more likelihood to suffer spinal cord injuries compared to skiers, with most of these injuries occurring during jumps and falls. Compared to non-aerial elements, a greater proportion of head/neck and trunk injuries occur on aerial elements in snowboarders (Russell et al., 2013, p. 174). These results align with the result of Carús and Escorihuela (2016a, p. 417) who found that the face is the most anatomical injury location on non-aerial elements, whereas, on aerial elements, the head is the most frequently injured location in skiers. The most common injury type in the TP appears to be fractures, although non-aerial elements contribute to more sprain/strain injuries and aerial elements result in a higher proportion of fractures (Carús & Escorihuela, 2016a, p. 418; Russell et al., 2013, p. 175; Russell et al., 2014, p. 25).

Steenstrup et al. (2014, p. 42), reported in their cohort study that head and face injuries accounted for 11,8% of all injuries with concussion being the most prevalent type of injury (81,6%). Of these head and face injuries, 47% led to absence from training or competition. Furthermore, the likelihood of experiencing head and face injuries was greater in freeski (5.5 per 100 athletes) and snowboarding (5.0), compared to alpine skiing (3.5). These outcomes are consistent with the findings of Carús and Escorihuela (2016a, p. 418), which observed a greater risk of concussion on aerial elements (13,6%), compared to non-aerial elements (4,3%). Furthermore, the most common injured body region on aerial elements was the head, face, shoulder, and wrist in both ski and snowboard, with similar results on non-aerial elements (Carús & Escorihuela, 2016a, p. 417; Russell et al., 2013, p. 175).

3.2.2 Sex differences

The literature indicates varied findings regarding the difference in injury risk and injury characteristics between sex. Soligard et al. (2015, p. 444) observed three times as high an injury risk in female Slopestyle skiers compared to male skiers in the Olympics in Sochi 2014, while no such difference was detected in snowboard Slopestyle. However, Palmer et al. (2021, p. 970), observed that female athletes had a significantly greater risk of sustaining an injury compared to male athletes in both snowboard Big air and Slopestyle. These findings align with the results by Russell et al. (2014, p. 3), which indicate that female snowboarders have a higher risk of sustaining severe injuries as well as an increased overall injury risk. According to the findings of Rugg et al. (2021, p. 6), male snowboarders were more likely to have shoulder and chest injuries, fractures, dislocation, and wounds, while female snowboarders had a higher incidence of injuries to the back and pelvis, as well as contusion, strains, and sprains. Furthermore, Steenstrup et al. (2014, p. 43), discovered that females had a higher risk ratio than males for sustaining head/face injuries in freestyle skiing and snowboarding. In contrast, Carús and Escorihuela (2016b, p. 88), indicate that a greater proportion of male skiers sustain injuries in the TP compared to female skiers. However, this paper reports the percentage of total injuries rather than the percentage of injured in relation to the proportion of individuals who made use of the TP. Thus, the results might be explained by the fact that a higher proportion of male individuals used the TP. This is supported by Goulet et al. (2007, p. 404), which indicate that there is no significant difference in the proportion of female and male individuals who sustain injuries relative to the proportion of users in the TP.

Major et al. (2014, p. 21) observed no sex difference in injury risk or injury characteristics within any World Cup snowboard disciplines. However, as shown by (Torjussen & Bahr, 2006, p. 231), the injury risk differs between the disciplines, where female athletes seem to have a higher risk for injuries in jump-related disciplines compared to male athletes, while the result is more similar in slalom disciplines. Possibly, the varying results could be attributed to differences in skill level and the difficulty level of the TP in the papers. Another hypothesis is that the features within the TP are designed to challenge the top male athletes and may be too demanding for certain female athletes (Steenstrup et al., 2014, p. 44). These presented findings are obtained from recreational athletes and may not be applied to the elite level. However, research indicates that men tend to be more thrill-seeking than women (Breivik et al., 2017, p. 269). This disparity in psychological factors could potentially account for the findings observed by Rugg et al. (2021, p. 3), where male snowboarders exhibited higher injury rates in advanced trails and an elevated risk of severe injuries compared to their female counterparts. This pattern may also extend to the elite level.

3.2.3 Skill level and injury risk

The literature suggests that elite athletes have a greater proportion of knee injuries, in contrast to recreational athletes who have a greater proportion of wrist injuries (Idzikowski et al., 2000, p. 829; Kim et al., 2012, p. 773; Major et al., 2014, p. 21; Rønning et al., 2001, p. 581; Steffen et al., 2017, p. 32; Torjussen & Bahr, 2005, p. 371). Research has concluded that wrist injuries make up 9% and 8% of injuries among national and elite athletes, respectively (Torjussen & Bahr, 2005, p. 375; 2006, p. 233). However, in recreational athletes, wrist injuries account for more than 20% of all injuries (Idzikowski et al., 2000, p. 829; Kim et al., 2012, p. 773; Rønning et al., 2001, p. 581; Torjussen & Bahr, 2005, p. 371). Elite athletes may be able to avoid falling on the wrist due to superior skills, edge control, and fall technique compared to recreational individuals (Torjussen & Bahr, 2006, p. 233). In snowboarding, both legs are fixed, which may reduce the risk of twisting the knee ligaments, minimizing valgus stress and thus reducing the likelihood of knee injuries. However, this benefit may be limited among elite athletes who perform aerial maneuvers on bigger and more spectacular jumps, as the impact and torsional forces increase upon landing (Major et al., 2014, p. 21; McNeil et al., 2012, p. 9; Swedberg & Hubbard, 2012, p. 129). This is supported by several papers, which have provided evidence that experts and higher skill levels have a greater incidence of severe injuries compared to novice users (Goulet et al., 2007, p. 404; Hubbard & Swedberg, 2012; Russell et al., 2014, p. 27). In contrast, Carús and Escorihuela (2016b, p. 88), discovered that novice individuals had a considerably greater risk of sustaining a severe injury compared to individuals with higher skill levels. Furthermore, Idzikowski et al. (2000, p. 827), found a greater proportion of injuries among novice snowboarders compared to those with an advanced skill level. However, these two papers do not state the percentage of injuries relative to the total number of users of the TP within the different skill levels. The omission of percentage breakdown by skill level in the study may be attributed to the plausibility that novice individuals using the TP lack awareness of their true skill level leading to a potential bias in self-estimating their abilities. However, it is conceivable that the majority of TP users possess a higher skill level, given that it requires a significant degree of balance and body control. The discrepancies in the results reported in the papers could stem from various factors, such as self-reported experience level bias, differences in the definition of experience level, variation in the complexity of the jump design, or potential underestimation of the actual occurrence of injury.

3.2.4 Terrain Park versus slopes

Injuries that occur in TP are more prone to result in fractures and concussions, with a higher proportion of trunk injuries compared to the slope (Brooks et al., 2010, p. 120; Goulet et al., 2007, p. 404). Furthermore, a higher likelihood of head, face, and back injuries is observed in the TP compared to the slope, whereas Goulet et al. (2007, p. 403) observed this pattern only in skiers. Injuries in the slope are more prone to result in bruises, sprains, strains, and dislocations with a higher likelihood of hip and shoulder injuries compared to the TP (Brooks et al., 2010, p. 120; Goulet et al., 2007, p. 404) . Additionally, a higher proportion of severe injuries that necessitate hospital transport are observed in the TP. Injured people in TP were also more likely to be self-proclaimed experts (Brooks et al., 2010, p. 120). Furthermore, skiers were more likely to sustain severe head and neck injuries, while snowboarders were more likely to sustain severe extremity injuries in the TP compared to the slope (Goulet et al., 2007, p. 404).

3.3 Jump design and mechanics

TP jumps are typically constructed by shapers who rely on their experience. While the shaper may test and make adjustments before the jump is opened to the public, there is usually little scientific analysis or detailed design planning before the construction (Hubbard, 2009, p. 175; Hubbard & Swedberg, 2012, p. 3; McNeil et al., 2012, p. 1; Swedberg & Hubbard, 2012, p. 122; Wolfsperger et al., 2021, p. 1083). New jumps are typically evaluated by professional staff riders who possess extensive knowledge about the potential risks of injury associated with both high and low take-off speeds depending on the jump design. In contrast, the limited awareness of risks among less experienced individuals within ski facilities can potentially lead to less experienced individuals utilizing jump designs with a high injury risk. As a result, the jump design should adhere to documented safe design principles and analysis methods that are derived from research (Böhm & Senner, 2008; Hoholm, 2022; Hubbard, 2009; Hubbard & Swedberg, 2012; Levy et al., 2015; Linløkken, 2022; 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., 2021) which includes comprehensive procedures for design, construction, and maintenance. While variations in equipment, rider behavior, and weather conditions also impact safety, they don't compromise the fundamental physical factors that should form the foundation of the design (Kulturdepartementet, n.d.).

The jump design process is complex. New technologies such as data modelling and simulation are constantly emerging (Levy et al., 2015; Moore & Hubbard, 2018) and can be useful tools to design jumps to enhance safety. To ensure a safe environment for athletes competing in Slopestyle and Big air, the jump measurements need to be calculated and account for various rider outcomes. This process begins by establishing the performance criteria, including factors such as the desired jump distance, minimum radial acceleration, and the maximum acceptable limit of EFH. Constraints are then listed, which may include the snow volume and the base area for constructing the jump. Using this information, a sketch of the jump is prepared, highlighting the interacting components, and estimating their relevant scales (length, with, and height). This allows for an assessment of whether the required amount of snow aligns with the sketch and snow budget. If adjustments are necessary, modifications of the component dimensions or the snow volume are made. Additionally, physical parameters such as friction, drag, lift, rider actions, and the athlete’s mass and weight are considered in the modeling of the jump design. By calculating various parameter ranges, the outcomes of the athlete trajectories are mapped out, along with the range of key performance characteristics. These results are then compared to the established performance criteria, and design changes are implemented accordingly. This process is repeated until the performance criteria align with the constraints, or adjustments are made to either the performance criteria (jump size) or the constraints (snow budget) (McNeil et al., 2012, p. 6).

The consensus in the literature is that the force an athlete must control during take-off and the force they must absorb during landing can result in imbalances that can compromise their control. These factors may increase the risk of injury, making them crucial design elements to secure the athlete's safety (Hubbard, 2009, p. 178; Hubbard & Swedberg, 2012, p. 3; McNeil, 2012a, p. 138; McNeil et al., 2012, p. 6; Swedberg & Hubbard, 2012, p. 122). Löfquist and Björklund (2020, p. 1567) found that skiers experience a force equal to twice their body weight when landing on a Big air jump. The force exerted on the musculoskeletal system during contact with the ground is known as the ground reaction force (GRF). Factors that influence the GRF include the weight of the athlete, the velocity, and the slope's curvature (Vernillo et al., 2018, p. 3). The center of mass (COM) in a normal standing adult is about 1 m and humans can tolerate falls in 1g of 1-2 meters (Hubbard, 2009, p. 179). Therefore, Hubbard (2009, p. 179) suggested that landing impacts should not surpass those resulting from a 1 meter drop onto a horizontal surface. The United State Terrain Park Council (USTPC) has established a maximum acceptable EFH limit of 1,5 m for all landing areas (McNeil et al., 2012, p. 8).

Jumps are supposed to be “safe” but at the same time provide an enjoyable, challenging, and exhilarating experience that preserves the integrity of the sport (McNeil et al., 2012, p. 16). Therefore, the jump design involves a trade-off between safety and excitement. The exhilaration is a product of flight time and air height, both a function of the horizontal distanced jumped and the jump design (Hubbard, 2009, p. 181; McNeil et al., 2012, p. 16). It is conceivable that modifying the jump design to prioritize safety could diminish the element of excitement. However, a study by Hubbard (2009) has shown that safe jump designs can maintain the exhilaration aspect with flight time and air height of 2s and 3m respectively, on jump lengths of about 30 m. This section will cover the various components involved in a jump, and how different jump designs can impact the safety of the athlete.

3.3.1 Jump components

A TP jump consists of several interacting components, such as the start, approach, transition, take-off, deck (maneuver area), landing, bucket and run out (figure 1) (McNeil et al., 2012, p. 3). Each section plays an important role and should be designed carefully, creating a safe and challenging environment for the athletes. The speed at take-off is determined by the location of the start relative to the take-off as well as the shape of the approach, transition, and take-off (McNeil et al., 2012, p. 3; Wolfsperger et al., 2021, p. 1082). Ignoring forces (friction and air drag), the maximum speed at take-off, also called the *design speed,* is determined by the difference in elevation between the start and the take-off lip (Levy et al., 2015, p. 229; McNeil et al., 2012, p. 3). It is common that the approach has a steep initial slope region (drop-in) followed by a more modest pitch region leading to the transition. The purpose of the approach is to provide the minimum speed necessary to jump over the knuckle (McNeil et al., 2012, pp. 3-4). However, as a consequence of various snow conditions and rider behavior, the athlete might lack sufficient speed at take-off to clear the knuckle, resulting in an impact on the deck (McNeil et al., 2012, p. 4).

The transition provides a smooth transformation from the approach to the take-off and must be carefully designed to prevent excessive radial accelerations on the athlete. The take-off lip is the final point of contact before jumping. It is crucial that this area is properly designed to avoid imbalance and dangerous inverting rotations. The athlete can adjust the flight trajectory (absorbing or pushing with the legs at take-off) and the angular momentum (start turning at the take-off) by adding muscular work at the take-off, commonly referred to as “pop” (McNeil, 2012b, p. 4; Wolfsperger et al., 2021, p. 1082). The maneuver area above the deck is where the athletes perform various advanced tricks while airborne. The length of the deck is determined by the location of the take-off and landing area. In their observation, Böhm and Senner (2008, p. 170) noted that shorter deck lengths and steeper landing angles led to increased landing impacts, due to the athletes landing on the flat part of the slope beyond the designated landing area. The knuckle is defined as the intersection point between the deck and the landing (McNeil, 2012a, p. 140). The steep part of the landing area around 2m beyond the knuckle, known as the "sweet spot," is the most desirable landing point (McNeil, 2012a, p. 146; McNeil et al., 2012, p. 7). Landing at the “sweet spot” will result in minimal impact on the athlete characterized by a smaller EFH, which will be beneficial for injury prevention. The bucket is the section where the slope flattens out from the landing towards the run-out. As a result of constant use, the bucket will accumulate snow, shortening the landing area. Maintenance procedures and increased landing length designs can be effective prevention strategies (McNeil et al., 2012, p. 4).

3.3.2 Kicker design

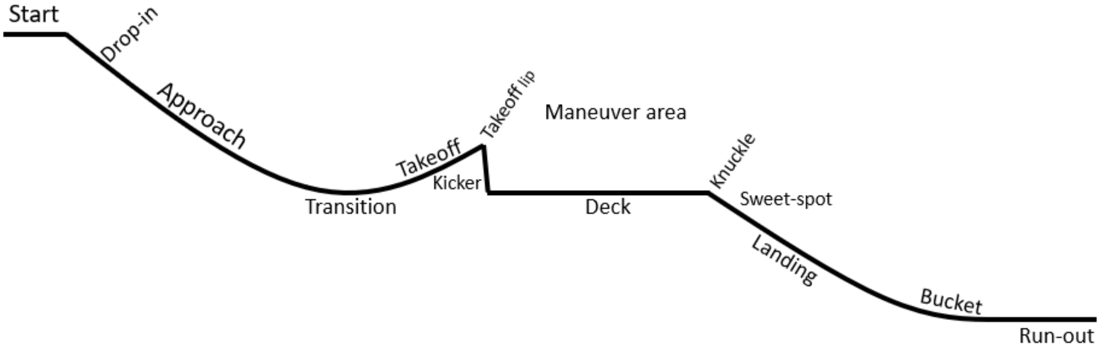

Figure 1: The geometry and interacting components of the standard table-top jump, modified illustration from McNeil et al. (2012, p. 4).

Rider actions and a concave curvature at take-off can induce dangerous inverting rotations, causing the athlete to land in an inverted position on the head, neck, or back that may lead to devastating injuries, especially for recreational users (McNeil, 2012a, p. 147; McNeil et al., 2012, p. 11). Bakken et al. (2011) identified that the primary cause of injuries in Snowboard Cross resulted from technical error at take-off. Swedberg (2010, pp. 52-62) demonstrates that an abrupt shift in perceived gravitational acceleration will be felt by the athlete at two transition sites in a circular curvature, which can disrupt the athlete’s balance and concentration while preparing to jump. McNeil et al. (2012, p. 4) recommend that the curvature of the transition is constructed in a way that the athlete experiences a maximum limit of excessive radial accelerations of 2g. Therefore, a concave curvature should be replaced by a straight section in the last part prior to the take-off lip, allowing the athlete to recover from the transition (McNeil, 2012a, p. 147; McNeil et al., 2012, p. 12). According to Schmidt et al. (2019, p. 159), the human response time is about ~0,2 s. The International Ski Federation (FIS) has, for this reason, established a criterion that the end of the take-off ramp should be straight for a distance equal to 0,25s times the nominal take-off speed for all Nordic jumps, while the USTPC has a standard criterion of 0,3 s (1.5 human reaction) times the nominal take-off speed (Levy et al., 2015, p. 234; McNeil, 2012a, p. 145; McNeil et al., 2012, p. 12).

The gravitational forces the user is exposed to on the kicker are affected by the take-off size. The compression felt by the athlete increases in line with the take-off speed, thus the height and length of the take-off should be adapted to the maximum possible speed, as well as the angle of the take-off (Kulturdepartementet, n.d.). It is primarily the curvature of take-off that is crucial to how the gravitational forces are distributed. Kulturdepartementet (n.d.) recommends that the take-off is designed with an elliptic curvature to achieve an even distribution of gravitational acceleration, where the radius of the curvature gradually decreases in line with the users speed closer to the take-off lip. In contrast to the elliptic curvature, both circular and coiled curvatures result in an uneven distribution of gravitational forces (figure 2). The circular curvature exhibit compression at the beginning of the take-off, while the coiled curvature exhibit compression towards the end of the take-off. Both of these compression patterns have the potential to disrupt the athlete’s balance, leading to potential imbalances during the airborne phase (Kulturdepartementet, n.d.). Experienced athletes, in contrast to less experienced individuals, possess the skill to intentionally execute inverting rotations and counterbalance the inverting rotation effect with a forward rotation (McNeil, 2012a, p. 145; McNeil et al., 2012, p. 11). Thus, less experienced users should have a smaller take-off angle (Kulturdepartementet, n.d.).

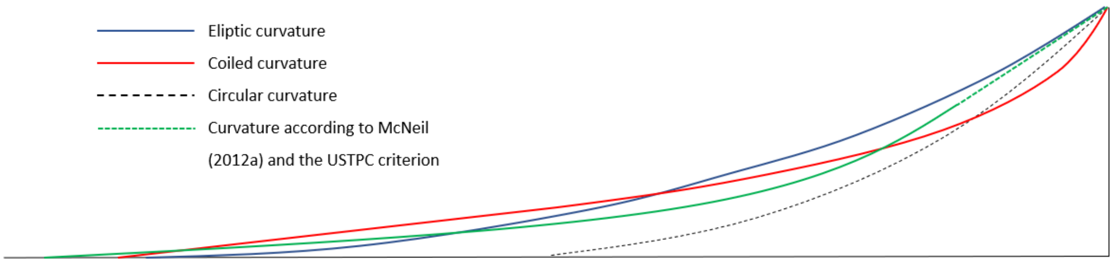

Figure 2: Modified illustration inspired by Kulturdepartementet (n.d.) of four different take-off curvature designs; elliptic curvature (blue solid line), coiled curvature (red solid line), circular curvature (black dashed line) and curvature according to McNeil (2012a) and the USTPC criterion (green solid line), with the straight section at the end of take-off (green dashed line).

3.3.3 Landing area

The start of the landing area is defined as the point where the maneuver area end (after the knuckle) or at the point where the parabolic shape transition to a landing surface with a constant downward slope (Kulturdepartementet, n.d.). The optimal landing point to reduce injury risk upon landing is called the “sweet spot”, which varies substantially in length depending on the choice of jump design (deck length, height of the take-off lip, take-off angle, landing angle and shape of the landing) (Kulturdepartementet, n.d.; McNeil et al., 2012, pp. 7-10). The velocity at take-off determines the flight path, the landing point, and the impact the jumper is exposed to upon landing (Levy et al., 2015, p. 230). Calculating the velocity at take-off can provide valuable information about the horizontal length of the jump necessary for the athlete to land in the “sweet spot”. However, evaluating the trajectory of an athlete is complex and there are several forces to consider. These forces include friction, aerodynamic drag, lift, and gravity (Hubbard, 2009, p. 176; McNeil & McNeil, 2009, p. 160; Wolfsperger et al., 2021, p. 1082). Adding “pop” at the take-off may also alter the take-off angle, the trajectory of the athlete, and the landing point (McNeil et al., 2012, p. 16). Ideally, to ensure the safety of the jumper upon landing, the deck and landing area design should accommodate the minimum and maximum take-off velocity. However, it is a challenge to find the optimal deck length and landing angle since individual differences in take-off velocity, rider actions and variations in take-off angle affect the flight trajectory of the jumper (Böhm & Senner, 2008, p. 165). Friction, drag, and lift are influenced by snow- and weather conditions, thereby change in external conditions may induce significant fluctuations in the take-off velocity and hence horizontal jump distance (McNeil et al., 2012, p. 4; Wolfsperger et al., 2021, p. 1085). Thus, changes in external conditions may lead to a significant impact upon landing, despite that the interacting components are designed in accordance with each other. However, as shown by Hubbard and Swedberg (2012), knowing the forces and rider actions that act on the jumper (“uncontrollable factors”) and incorporating these in the jump design, one can calculate the optimal position of the take-off and landing so the jumper land in the “sweet spot”(soft landing region).

Several papers highlight mainly two reasons which lead to the greatest risk for impact injuries; either due to landing short on the deck or knuckle, or over-jumping the intended landing region, where the jumper in both cases lands on a flat surface (Böhm & Senner, 2008, p. 173; Hubbard & Swedberg, 2012, p. 6; Levy et al., 2015, p. 228;

McNeil, 2012b, p. 10; McNeil et al., 2012, p. 4; McNeil & McNeil, 2009, p. 160). According to research, a significant portion of severe spinal cord injuries (SCI) sustained in TP is a consequence of over-jumping the intended landing area. Thus, over-jumping is a critical factor to insure cannot occur (Hubbard & Swedberg, 2012, p. 6; McNeil et al., 2012, p. 16). According to McNeil et al. (2012, p. 5), a recommended preventive measure for avoiding overshooting the landing and achieving the appropriate speed to land in the sweet spot is to have multiple starting points and select the most suitable one based on weather and snow conditions. Furthermore, the impact upon landing depends only on the component of the velocity vector perpendicular to the landing surface. By designing a landing surface angle that closely matches the angle of the jumper’s flight path, the impact upon landing can be substantially reduced regardless of landing speed (Hubbard, 2009, p. 178; Hubbard & Swedberg, 2012, p. 3; Levy et al., 2015, p. 230; McNeil et al., 2012, p. 6). The landing surface angle should match or be slightly steeper than the take-off angle, as gravity and aerodynamic forces result in a slightly steeper descent angle than the take-off angle (Kulturdepartementet, n.d.).

3.3.4 Different jump designs

In specific jump designs like table-top and step-down jumps, the maneuvering region encompasses a flat section followed by a distinct knuckle (figure 3). However, roll-over and step-up jumps lack a definite flat part or knuckle in favor of a parabolic shape that follows the athlete's jump trajectory up to the point which the landing commences with a constant downhill slope (Kulturdepartementet, n.d.). To indicate a roll-over, the top of the maneuvering area should be equal in height to the take-off lip, or slightly higher (100–120% of the take-off lip's height). The step-up is distinguished by the maneuvering area and the beginning of the landing being at a higher elevation than the take-off lip. Parabolic-shaped jumps offer several advantages in terms of safety. As the landing occurs at a reduced velocity and the maneuvering area aligns with the athlete's trajectory, those who jump short experience minimal impact upon landing, unlike other jump designs. However, due to the shorter airtime, these jumps limit the athlete’s ability to execute maneuvers. The design must consider the possibility of the athlete reaching a maximum speed that can cause them to overshoot the landing, resulting in potentially hazardous landing impacts (Kulturdepartementet, n.d.).

The table-top is the most commonly built jump, due to the ease of construction and simplicity to fabricate (McNeil et al., 2012, pp. 3-12). The tabletop doesn't limit the athlete's ability to perform maneuvers. However, it poses fundamental safety issues, as it is not optimal for limiting landing impact characterized by EFH, as jumpers frequently jump short and land on the deck (McNeil, 2012a, p. 141; McNeil et al., 2012, pp. 3-7). Aside from the shape of the maneuvering region, the table-top bears many similarities to the roll-over. The step-down is characterized by the maneuvering region and the landing is situated considerably lower than the take-off lip, leading to a shorter landing and "sweet-spot" (given the underlying slope is unchanged), as compared to other jump designs (Kulturdepartementet, n.d.). Due to difficulty in adjusting the correct speed, athletes tend to land heavily and absorb large landing impacts, thereby increasing the risk of injury. However, the step-down offers longer airtime and greater opportunities for performing spectacular maneuvers. The step-down jump requires exceptional skills and the ability to consider the appropriate speed and is therefore not recommended in public ski facilities (Kulturdepartementet, n.d.).

As indicated, certain jump designs entail a greater potential for injury in the event of a miscalculation of speed. Ski facilities should possess an understanding of the advantages and disadvantages associated with various jump designs and select a design that aligns with the skill level and assessment abilities of the intended user group.

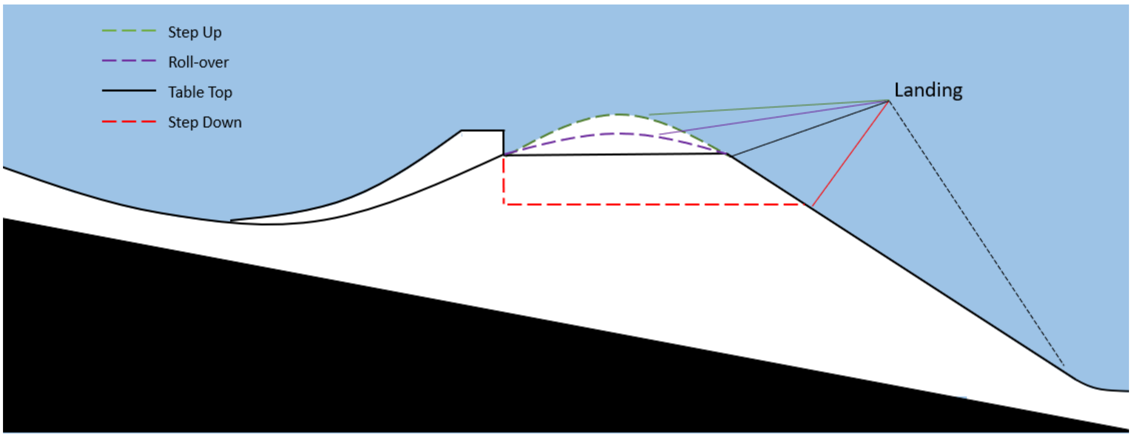

Figure 3: Shows four different jump designs inspired by Kulturdepartementet (n.d.); Step down (red dashed line), Table-top (black solid line), Roll-over (purple dashed line) and Step up (green dashed line) and their respective landing areas (given the underlying slope is unchanged).

3.4 *Landing stability as a surrogate measure*

Van Mechelen et al. (1992) four-step “sequence of prevention” is a widely recognized and utilized framework for assessing the extent of sports injuries and the effectiveness of implementing preventive measures (figure 4). However, in elite sports, a small sample size may perhaps weaken the statistical power of the findings, increasing the risk of making a type II error (Kröll et al., 2017, p. 1644). According to Kröll et al. (2017, p. 1645), classic statistical testing is not suitable for evaluating prevention measures in elite sports with small sample sizes, as the findings in the fourth step of the model are likely to be underpowered. One potential solution is to employ a surrogate measure that encompasses not only the intended event being measured but also other situations that are frequently associated with the event. Hence, in this thesis, it is necessary to utilize a surrogate measure that encompasses not only the occurrence of the actual injury itself but also injury-related situations. This approach will result in a larger number of observations, subsequently enhancing the statistical power of the study. However, this is only valid if the surrogate measure is frequently associated with the injury (Johnsson et al., 2018, p. 766; Kröll et al., 2017, p. 1645).

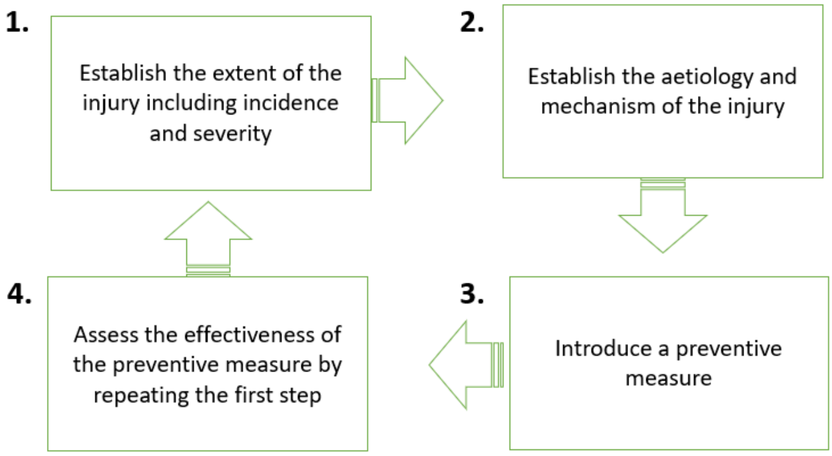

Figure 4: Modified illustration from Van Mechelen et al. (1992, p. 84) of the four-step “sequence of prevention” of sport injuries.

Bakken et al. (2011, p. 1317) investigated the mechanism of injury in a snowboard cross world cup event. Their findings indicate that most injuries were associated with the athlete’s loss of control, which was primarily due to technical error, often resulting in a fall. Randjelovic et al. (2014, p. 32) found similar findings in freestyle ski cross, where every injury was related to the loss of control and stability, which in most cases resulted in a fall. In summary, these studies show that the risk of injury is frequently related to instability and falls during landing. Furthermore, multiple other articles suggest that the risk of injury is closely associated with falling and landing when jumping (Brooks et al., 2010, p. 120; Carús & Escorihuela, 2016a, p. 417; Moffat et al., 2009, p. 259; Russell et al., 2013, p. 174; Russell et al., 2014, p. 26). Thus, landing stability is a valid surrogate measure to investigate how different rider behavior factors affect the injury risk upon landing in this thesis.

3.5 Injury risk factors

Injury risk factors refer to factors that can impact the likelihood of experiencing an injury. These factors include equivalent fall height, variables and forces that affect velocity, and rider behavior.

3.5.1 Equivalent fall height

According to research, the injury rate in Slopestyle and Big air in freeski and snowboard is high, with jumps causing severe injuries due to the high impact upon landing. The energy absorbed upon landing is one of the most crucial factors affecting the safety of a jump. Several papers have used the concept of EFH to describe this parameter (Hubbard & Swedberg, 2012, p. 79; Levy et al., 2015, p. 229; McNeil et al., 2012, p. 6; Moore & Hubbard, 2018). Moore and Hubbard (2018, p. 818) define 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". In other words, the injury risk upon landing is related to the impulse necessary to bring the velocity component of the athlete perpendicular to the landing surface to zero (Swedberg & Hubbard, 2012, p. 122). The fall height (h) of the athlete is related to the velocity (v) at impact by the equation $h = v^2/2g$, where g is the gravitational acceleration. However, when jumping and landing on a sloped landing, only the velocity component perpendicular to the landing surface ($v_\perp$) must be brought to zero, resulting in the equation: $h = v_\perp^2/2g$ (Hubbard & Swedberg, 2012, p. 77; McNeil et al., 2012, p. 6).

The EFH can give us valuable information about the injury risk upon landing. A small EFH will lead to softer landings due to smaller perpendicular velocity, which will be beneficial for injury prevention. In situations where the athlete has large landing speeds, the EFH can be limited (made arbitrarily small) by making the angle of the landing surface closely match the jumper`s flight path. The component of the landing velocity normal to the landing surface is a product of the jumper`s landing speed (v) and the difference between the landing slope angle and the flight path angle (v sin). This equation is given by $V_{\perp} = V_{J} sin\ (\theta_J - \theta_L)$, where θ_J is the jumper`s landing angle and θ_L is the angle of the slope (Hubbard & Swedberg, 2012, p. 77; McNeil et al., 2012, p. 6; Swedberg & Hubbard, 2012, p. 122). Thus, the expression for EFH is:

$$EFH = \frac{V_J^2\ sin^2\ (\theta_J - \theta_L)}{2g}$$

As far as we know, there haven't been any studies exploring the direct correlation between EFH and injuries. However, several studies have assessed the impact upon landing in relation to various take-off velocities and landing surface angles but are mainly based on results from computer simulation and modeling (Böhm & Senner, 2008; Hubbard, 2009; Hubbard & Swedberg, 2012; McNeil, 2012b; McNeil et al., 2012; McNeil & McNeil, 2009; Moore et al., 2021; Swedberg & Hubbard, 2012). Four studies have collected empirical data on the impact upon landing (Hoholm, 2022; Hubbard et al., 2015; Linløkken, 2022; Petrone et al., 2017). Linløkken (2022) research marked the pioneering investigation linking EFH and rider behavior with landing stability in a Slopestyle world cup event. As far as we know, this study stands as the second of its kind to examine this relationship. Furthermore, it represents the first study to investigate this relationship in the context of a Big air event.

3.5.2 EFH criterion

The result from Minetti et al. (1998, p. 1789) indicates that EFH of h= 1.5 m is the maximum value an elite jumper can absorb in the legs. Thus, landing impacts that exceed EFH greater than h=1,5 m cannot be considered safe (Petrone et al., 2017, p. 290). High values of EFH up to 10 m have been observed in large table-top jumps, which may explain the high risk for severe injuries observed in these two disciplines (Hubbard & Swedberg, 2012, p. 11; Petrone et al., 2017, p. 290). Swedberg and

Hubbard (2012, p. 129) demonstrated that the values of EFH increase linearly with the horizontal jumping distance in a table-top jump. The EFH also increases substantially with larger take-off heights and take-off angles. The table-top design can only be considered safe if the jumper land in the soft-landing region, which research has shown to be relatively short (Böhm & Senner, 2008, pp. 5-8; McNeil et al., 2012, pp. 8-9; Swedberg & Hubbard, 2012, pp. 129-132). Thus, the table-top design is sensitive to velocity and may result in large EFH values if the jumper is unable to control the landing point through the proper choice of take-off velocity.

3.5.3 Constant EFH landing surface and feasibility

Given that the table-top do not adequately ensure the athlete's safety due to large impacts upon landing, a theoretical approach for a more optimal landing surface design that limits the impact upon landing has been developed (Hubbard, 2009; Hubbard & Swedberg, 2012; Levy et al., 2015; McNeil et al., 2012; McNeil & McNeil, 2009). This approach is based on shaping the landing surface so the perpendicular velocity component is small at every possible impact site (Moore & Hubbard, 2018, p. 818). This landing surface is referred to as a "constant EFH landing surface" where the deck is replaced in favor of a parabolic landing zone (maneuver area treated as part of the landing), with a smooth transition to a straight line run-out (Hubbard & Swedberg, 2012, p. 78; McNeil & McNeil, 2009, p. 163)(figure 5). The "constant EFH landing surface" has a landing surface angle that continuously decreases with the horizontal jump distance, which moderates the landing impact over a wide range of launch speeds (Hubbard, 2009, p. 180; McNeil & McNeil, 2009, p. 163).

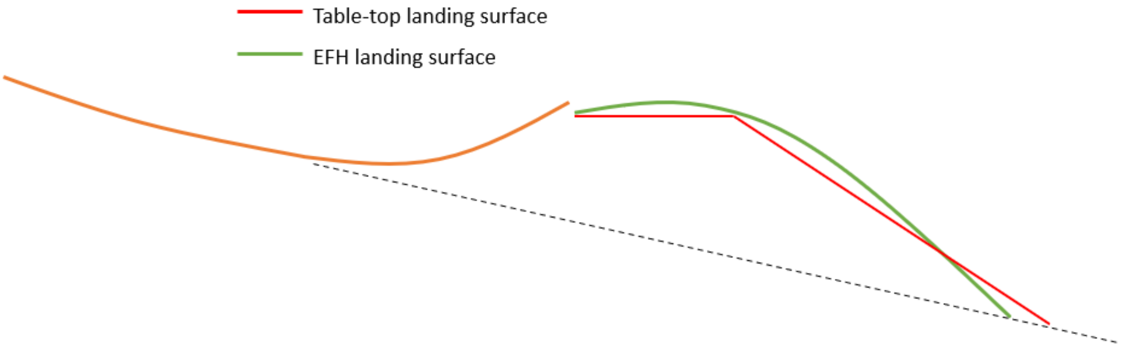

Figure 5: Modified illustration from (McNeil & McNeil, 2009) showing two possible landing surfaces; a standard table-top landing surface (blue dashed line) and a constant EFH landing surface (green line). The EFH landing surface has a parabolic landing zone with a smooth transition to a straight line.

The modified illustration from Moore et al. (2021, p. 7) demonstrates how the EFH in a table-top increases with horizontal jump distance and is lowest at the “sweet spot” at approximately 15 meters from the take-off (figure 6). Moreover, the EFH exceeds the USTPC criteria at most landing locations which illustrate the potential impact hazard of the table-top. However, the fact that EFH is kept constant in a parabolic landing shape regardless of take-off velocity or landing location, as shown in the figure, highlights the benefits of such a design.

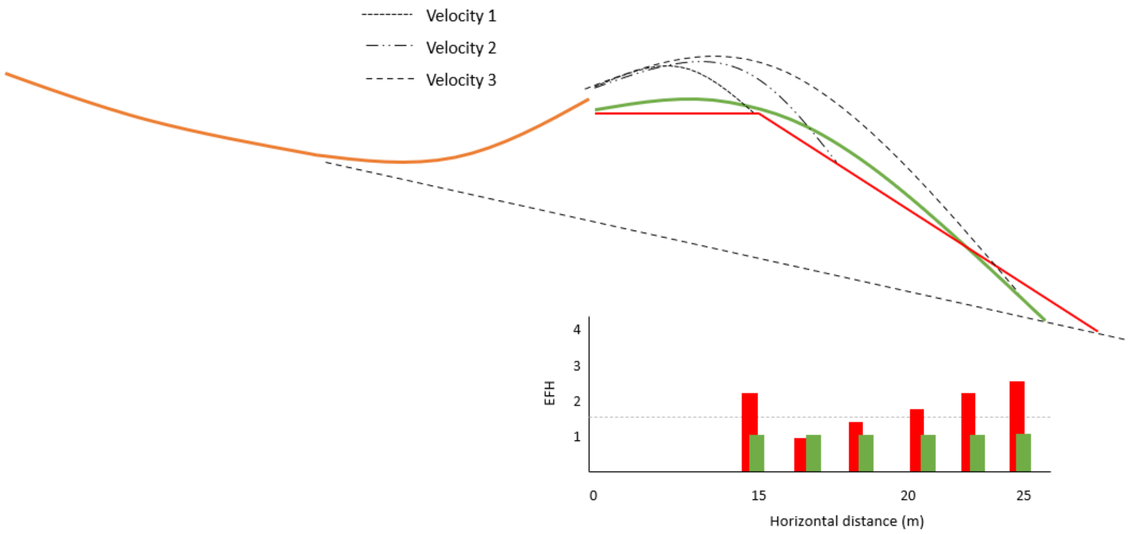

Figure 6: Modified illustration from Moore et al. (2021, p. 7) demonstrate how EFH changes (red bars) and exceeds the USTPC criterion (grey horizontal dotted line) in several landing points on a standard table-top landing surface (blue dashed line), and how EFH is kept constant at 1m (green bars) with a parabolic landing shape (green line). The dashed and dotted lines (black) represent the flight paths with different velocities, landing at the knuckle (velocity 1), the sweet spot (velocity 2), and towards the end of the landing (velocity 3).

Ski resorts have questioned the feasibility to make these jumps due to variations in snow- and weather conditions and rider actions (“uncontrollable factors”), as well as the high snow budget needed to allow for long landings (Hubbard & Swedberg, 2012, p. 76; McNeil et al., 2012, p. 5; Petrone et al., 2017, p. 284). On the contrary, Hubbard and Swedberg (2012) demonstrated that these “uncontrollable factors” are either irrelevant to the design, can be ignored, or directly incorporated into the design process. They also state that a "constant EFH landing surface" with a predetermined EFH value is insensitive to take-off velocity and landing point. Therefore, this design could prove advantageous for ski resorts which have jumpers with a large variation in skill level, as the EFH value remains unchanged regardless of the take-off velocity chosen. Petrone et al. (2017) presented evidence that designing jumps with low EFH values in medium size jumps (horizontal jump distance 6,3-12,6 m), is practical to build and function as intended by reducing the landing impact. It has also been questioned if these jumps will be big enough to provide exhilaration felt from long flight times and jump air heights (Hubbard, 2009, p. 181; McNeil et al., 2012, p. 16). However, the results of Hubbard (2009, p. 181) indicate that it is possible to build jumps with flight times and air heights of 2s and 3m in jumps up to 30 meters that maintain exhilaration and adequate safety upon landing.

However, a “constant EFH landing surface” is not without limitations. Practical speaking, the grooming equipment can only function up to an incline angle of 30C°, without using a winch (Hubbard, 2009, p. 180; McNeil et al., 2012, p. 14). Another limitation is the snow budget which can be insufficient for the landing lengths necessary to keep the EFH constant (McNeil et al., 2012, p. 10). However, given specific values for the jump parameters, it is possible to construct multiple EFH landing surfaces, with the one closest to the underlying slope being the least expensive to build. Therefore, if sufficient space is allocated to the jump design, it is always possible to identify a feasible constant EFH surface. (Hubbard, 2009, p. 180; Levy et al., 2015, p. 233; McNeil et al., 2012, pp. 14-15). Thus, modeling enables the construction of choosing the optimal landing area that meets the performance criteria, snow budget, safety considerations, and terrain constraints (McNeil et al., 2012, p. 19).

3.5.4 Factors affecting the inrun and flight trajectory

Several factors affect the take-off velocity and flight trajectory of the athlete. The shape of the approach determines the energy to accelerate the athlete by gravity (Wolfsperger et al., 2021, p. 1082). Assuming friction remains constant, the mass discrepancy among athletes will lead to an increase in kinetic energy for the heavier ones during the in-run. As a result, they will achieve greater take-off velocities and cover more horizontal distance in their jumps, which highlights the impact hazard with a short landing region.

Friction decelerates the athlete while in contact with the snow surface and is more difficult to facilitate when designing a jump. The friction coefficient affects the ability to accumulate velocity during the in-run and is influenced by several factors; the mass of the athlete, equipment, and snow condition (Hubbard & Swedberg, 2012, p. 80). The range of kinetic friction roughly falls between 0.04µ to 0.12µ, but it may exceed this value under exceptionally wet conditions (McNeil et al., 2012, p. 5). Despite their efforts, McNeil et al. (2012, p. 11) were unable to find a table-top landing surface with an EFH below 1,5 m under both low and high friction. This highlights the advantage of employing a “constant EFH surface” that remains unaffected by take-off velocity and snow friction, and maintains a consistent EFH during landing (Hubbard & Swedberg, 2012, p. 6).

By adjusting their body posture and clothing, athletes can manipulate air resistance (including air drag and lift) and regulate their take-off speed (Wolfsperger et al., 2021, p. 1083). Variations in wind conditions can cause substantial changes in air resistance, which influence the take-off speed, and thus the horizontal jump distance. According to (McNeil, 2012b, p. 6), head and tail wind of about 9m/s at a 20m jump with a take-off velocity of 15m/s, the horizontal jump distance varies from -14,4% to +8,5% respectively. Furthermore, Hubbard and Swedberg (2012, p. 81), found that a head- and tailwind of only 6 m/s is enough to substantially change the jumping distance. However, drag and lift effects can be neglected in small jumps (> ~12 m) and still provide accuracy of the jumper’s trajectory within the 10% and 1% level respectively (Hubbard & Swedberg, 2012, p. 7; McNeil, 2012b, p. 6). However, Big air and Slopestyle events feature larger jumps that provided significant airtime, making it essential to include air resistance when conducting simulation. The paper by Wolfsperger et al. (2021) provides valid input parameters of air resistance that can be used in these disciplines. According to their findings, altering posture and apparel can significantly influence air resistance for skiers, whereas the effect on snowboarders is less significant. Furthermore, posture affected air resistance to a larger extent than apparel. The paper suggests that snowboarders have a limited ability to manipulate their frontal area and compensate for low speeds, likely due to their balance mechanics (Wolfsperger et al., 2021, pp. 1084-1085). Consequently, a certain range of the landing surface is necessary to compensate for mass differences, snow- and wind conditions, and snow friction (Wolfsperger et al., 2021, p. 1085).

3.5.5 Rider behavior

Rider behavior includes a variability of different rider actions prior to the take-off, in the air, and upon landing (McNeil et al., 2012, p. 19). As shown by Linløkken (2022, pp. 66-67) rider actions affect the landing stability dependent on the choices of maneuvers and rotations. Better knowledge of the range of rider actions in relation to the intended user group would greatly improve our understanding of how different rider groups interact with winter TP jumps, as well as improve the validity of the design process simulation.

Pop

The most common and sensitive rider variable is when the jumper adds muscular work at the take-off lip which is referred to as “pop”. Adding “pop” alters the velocity vector, both in magnitude and direction, which increases the horizontal jump distance and results in different EFH values upon landing (Hubbard, 2009, p. 177; Hubbard & Swedberg, 2012, p. 9; McNeil, 2012b, p. 5; McNeil et al., 2012, p. 16). Athletes "pop" for two reasons: either to adjust their take-off speed to land in the “sweet spot”, or to improve their airtime and overall performance. According to McNeil (2012b, p. 7) the “pop” results in a change in take-off speeds from -2,48 m/s to +1,12 m/s. The result of Hoholm (2022, p. 68) indicates a larger positive pop range of up to +2,2 m/s. The skill level of the participant in (McNeil, 2012b) is unspecified, whereas in (Hoholm, 2022), the participants were elite athletes. Thus, the “pop” range values may differ substantially between different user groups (Hoholm, 2022, p. 85). Positive values refer to the situation where the jumper applies muscular effort to increase their velocity vector, while negative values occur when the athlete absorbs and decreases the take-off angle. The EFH for the “constant EFH surface” is only held constant if the athlete leaves the take-off at the same angle as the design assumes (Hubbard & Swedberg, 2012, p. 9; McNeil et al., 2012, p. 17). Thus, it is important to include the range of “pop” values in the simulation of the jump design. However, “constant EFH landing surface” designs have been shown to give acceptable EFH values regardless of the take-off speed including the athlete’s “pop” effects (McNeil et al., 2012, p. 20).

Complexity of maneuvers

As previously mentioned, the level of complexity in maneuvers enhances the level of difficulty, which is a judging criterion, resulting in a higher score (Fédération

Internationale de Ski, 2019, p. 12). It is conceivable that the complexity of maneuvers is influenced by various factors, including the number of rotations, the direction in which the rotation occurs, the orientation during take-off and landing, and the rotational axis. Moreover, it is plausible to consider that an escalation in maneuver complexity can result in a higher likelihood of encountering bad landing stability.

Angular velocities were calculated based on the number of rotations divided by airtime and describe the velocity of the rotation. The number of rotations and airtime were obtained through observational assessment. As the angular velocity increases, the complexity of the maneuver escalates, as the athlete has less time to orient themselves in the air and during landing. Additionally, the athlete must generate more momentum on the take-off lip. Nevertheless, this could increase the likelihood of bad landing stability, as the athlete would need to resist a higher momentum to maintain balance upon landing. The axis of rotation can also increase the complexity of the maneuver and can be performed around one or several axes. When rotating only around the longitudinal axis, the athlete performs the rotation in the transverse plane, with their legs beneath them. Rotations around the frontal axis occur in the sagittal plane and involve forward or backward flips. Rotations around the sagittal axis take place in the frontal plane and involve side flips. When the axis of rotation is multiple or off-axis, the athlete combines flipping and spinning, which can increase the level of difficulty as they must adjust their position within a more intricate context. However, off-axis maneuvers do not necessarily increase the complexity of the maneuver (Fédération Internationale de Ski, 2019, p. 12). Rotation around only one axis may be more challenging than an off-axis rotation of the same degree. This is because the athlete would need to resist a larger angular momentum upon landing, as opposed to it being distributed across multiple axes. Furthermore, during an off-axis rotation, the athlete may have a better perspective of the landing area throughout the maneuver.

Rotational direction concerns snowboarders and includes frontside and backside rotation. In a frontside rotation, the athletes are rotating from the heel edge and are facing downhill 90 degrees into the rotation. In a backside rotation, the athletes are rotating from the toe edge and are facing uphill 90 degrees into the rotation. There is a valid argument to suggest that executing a frontside rotation presents a greater challenge than performing a backside rotation. This assertion is based on the understanding that during a backside rotation, the athlete lands on the toe edge, which may introduce a greater degree of freedom and joint complexity. This could potentially enhance the athlete’s overall edge control, resulting in increased stability. However, Kurpiers et al. (2017, p. 2459) found that backside rotation led to a greater incidence of falls compared to frontside rotation. Disregarding the biomechanical variance between the rotational directions, executing rotations that result in blind landings, where the athlete has limited visibility of the last 180 degrees prior to landing, presents a greater level of difficulty. Rotational direction for skiers will not differ in technique. Nevertheless, spinning in all directions may not pose a challenge for either elite skiers or snowboarders, as it is one of the factors when judging difficulty.

Rider orientation during take-off and landing might also affect the difficulty and landing stability upon landing. In freeski, rider orientation at take-off and landing is divided into normal and switch. Performing a maneuver can vary in technique depending on whether you stand in a normal or switch position. Switch orientation during landing and take-off could potentially increase the level of difficulty as the athlete has limited view and needs to rotate their upper body to adjust their posture. However, neither Linløkken (2022, p. 66) nor Löfquist and Björklund (2020, p. 1567) found a difference in landing impact between normal and switch orientation during landing. In snowboard, normal rider orientation is when the athlete has their dominant foot in the front, and switch is referred to when their dominant foot is in the back. Although snowboarding has less variation in rider orientation technique compared to freeski, the difficulty level can increase during switch orientation, where athletes have less control because their dominant foot is positioned in the back. According to Linløkken (2022, p. 67) switch orientation during landing increased the likelihood of bad landing stability in snowboarding.

Consequently, by challenging these factors and increasing the complexity of the maneuver, performance can be improved, but the risk of injury is also likely to increase.

3.5.6 Sex difference

Sex is used as a proxy for all factors that could potentially affect the diversity in landing results among male and female athletes. It is widely acknowledged that males typically exhibit greater weight and higher lean mass in comparison to females (Schorr et al., 2018, p. 4). Male athletes are more likely to achieve higher velocities at take-off with the same approach length, due to their greater mass and the effect of gravity. Additionally, their higher muscle-to-mass ratio and leg strength may enable them to generate more momentum at the take-off and better withstand the impact upon landing. According to Hoholm (2022, p. 72), male athletes pop more than females in both freeski and snowboard which result in longer flight times.

Brooks et al. (2010, p. 120) demonstrated that a significantly greater number of male individuals sustained injuries in the TP in comparison to female individuals, whereas the discrepancy between sex was relatively minor on the slope. This might indicate that a greater proportion of male individuals make use of the TP and thus have a greater advantage in relation to the competitive environment and skill development. According to Breivik et al. (2017, p. 268), physiological factors play a crucial factor in the motivation and willingness to take part in risky activities. The study highlights a sex difference, with men exhibiting a higher propensity for thrill and risk-seeking activities. This might explain the result of Rugg et al. (2021, p. 3), which indicate that male snowboarders sustained more injuries on slopes with a higher level of difficulty compared to female snowboarders. Media coverage and differences in prize winnings may perhaps be other influencing factors that contribute to differences in participation and motivation. It is therefore probable that factors other than the physical ones, such as physiological and environmental factors, are responsible for differences in the pace of evolution of the sport between sex.

4. Methods

4.1 Participants

In this project, there were a total of 97 elite athletes including both males (n: 65), females (n: 32), skiers (n: 26), and snowboarders (n: 71) (table 1). Anthropometric data (height and mass) was collected before the competition, including clothes and equipment to calculate the true mass of the athlete during the competition. All participants were informed about the purpose of the project and gave their written consent before the data collection.

Table 1: Distribution of the participants in Mönchengladbach

Mönchengladbach	Male	Female	Total
Ski	16	10	26
Snowboard	49	22	71
Total	65	32	97

4.2 Data collection methodology and measurement protocol

The data collection took place in a Big air World Cup event in Mönchengladbach, Germany in December 2016 (2016/2017 season). The data from Mönchengladbach consist of one recorded jump that was used in qualification and finals for both disciplines. A total of 287 runs were recorded using a geodetic video method and were included in this thesis. Figure 7 shows the jump. The data collection methodology and measurement protocol employed in this thesis are identical to previous studies (Hoholm, 2022, p. 43; Linløkken, 2022, p. 44).

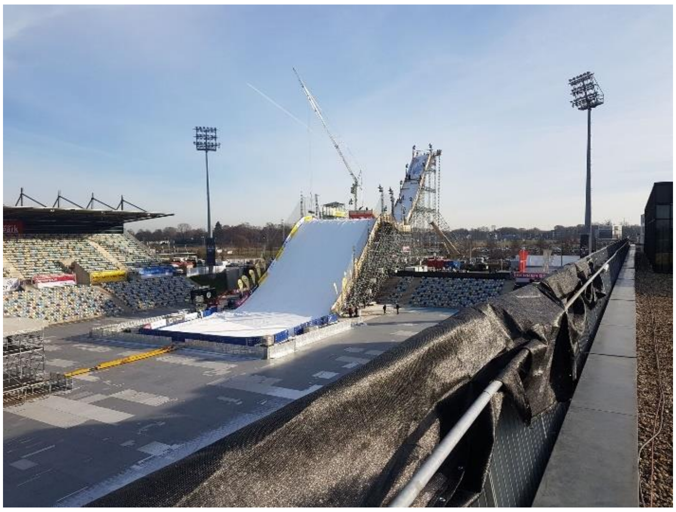

Figure 7: A picture of the construction of the scaffolding built Big air jump in Mönchengladbach

4.2.1 Infield collection of the physical data

The data was collected using the QDaedalus surveying method (QDaedalus, Geodesy and Geodynamics, ETH Zurich, Zurich, Switzerland), a tachymeter-based measurement system (figure 8). This system consists of two Leica tachymeter stations (Leica Total Station T1800, Leica Geosystems AG, Heerbrugg, Switzerland) with an attached CCD camera (AVT Guppy F-0 80C) and a GPS-antenna (ANN-MS-0) (Hauk et al., 2017, p. 295). The GPS antenna is connected to an interface box which is responsible for the communication between the components and enables tagging of the images with GPS time. The Leica station contains an external steering mechanism that allows actively control of the server motors in the horizontal and vertical angles of the total station telescope orientation, to track the athlete during the run.

The two stations were placed in two separate locations approximately 300 meters from the course, recording both the front and side perspective and providing images in black and white (figure 8). By using the forward intersection method between the direction vectors of the QDaedalus, the 3D-positions of the athletes' trajectories can be determined. When using the forward intersection method, one must have a local geodetic network, the position (coordinates) of the two QDaedalus stations, and a reference point. The reference point was set in a position visible from both total stations. The global position of the QDaedalus total station and the reference point was measured using a differential global navigation satellite system (dGNSS). The local geodetic network along with the baseline and global orientation of the total stations were established by measuring the angle and distance between the total stations and the reference point with the tachymeter-based measurement system and used to reconstruct the 3D position of the athlete's COM-position.

Figure 8: The left picture shows the placement of the two total stations (red circles), and their direction of measurement (red lines) in relation to the slope. The right picture shows the tachy-meter based camera system.

The Lidar laser scanning method (Pegasus backpack, Leica Geosystems, Heerbrugg, Switzerland) was used to capture the snow surface of the course and 3D-wind velocities were measured using two ultrasonic anemometers (Model 8100, R. M. Young Company, United States) recording at 1 Hz.

4.3 Data Processing and computation of jump mechanics

4.3.1 Computer vision

Images captured by the QDaedalus total station were used to locate the position of the athlete's COM within each image frame. Computer vision (CV) was applied to automatically annotate the COM-position of the athlete throughout the run and relied on a feature pyramid network (FPN) (Lin et al., 2017). The model used the CV library of Detectron 2, which provides object detection and segmentation algorithms (Wu et al., 2019). A mask was added using QDaulus and MATLAB (MathWorks Inc., Natick, MA, USA), decreasing the area the athlete could be present. The mask subtracted the background grey, avoiding background noise interference with the targeting object, making it easier for the CV to locate the athlete.

The CV consists of two separate stages. First, the algorithm detects the athlete in the image followed by a bounding box being placed around the object, limiting the area where the athlete can be present. In the second stage, a pose estimation algorithm predicts the position of the limbs and joints of the athlete and their coordinates within the bounding box (figure 9). Based on the position of the limbs of the athlete and their weight, one may determine the athlete`s COM position using the Zatsiorsky segment parameter model adjusted by de Leva (1996, p. 1228). This process was performed on each video frame in all the runs.

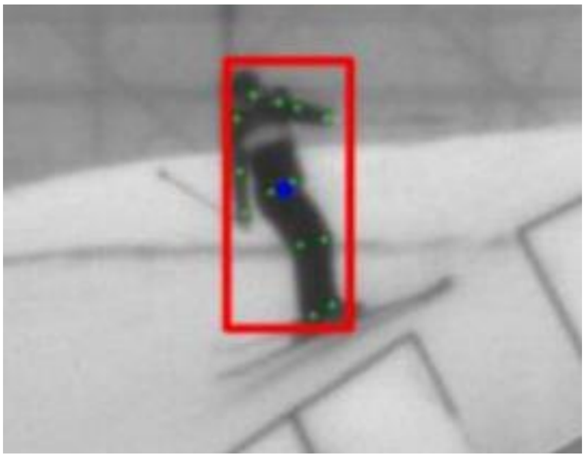

Figure 9: An example of the output of the prediction from the CV model with the bounding box (red box), estimated joint position (green dots) and the calculated COM-position (blue dot). Retrieved from the CV model in Seiser Alm, which are identical to the procedures followed in this project.

4.3.2 Manual annotation

However, due to low contrast in the black and white pictures, CV had in some situation's difficulty distinguishing the athlete from the background and estimating the COM accurately. As a result, none of the videos were completely automatically annotated. This issue was solved by manual annotation using QSecAnalysis software (QDaedalus, Geodesy, and Geodynamics Lab ETH Zurich, Zurich, Switzerland). For manual annotations, only the apparent COM was annotated, and the athlete's hip was defined as the guideline. The athlete's trajectories were calculated based on the average COM of each position in the air, using a cubic spline filter. The manual annotation process involved two individuals who followed predetermined guidelines to accurately position the COM relative to the hip, arms, and legs. In images where it was not possible to identify the athlete, no point was set.

4.3.3 Reconstruction of the athlete’s COM as 3D-position

The annotated COM-positions from the QDaedalus recordings from the two total stations in addition to the tracking information of the QDaedalus (position, angle, and time-based GPS synchronization) were used to locate the athlete’s position in 3D space using the forward intersection method.

Custom-made software was established in MATLAB to calculate the 3D position of the athletes in each image frame. The forward intersection method was based on the direction and position measurements from the two total stations recorded by the dGNSS, the angle measurements of the total stations to the athlete, the GPS time-based synchronization of the total stations, and the annotated COM image coordinates. The direction vector of the QDaedalus, through the lenses of the CCD cameras, was used to locate the intersection of the camera centers in the image. The direction of the total stations represents the angle between the baseline and the recording direction of the total stations to the athlete’s COM position (∠Ts1 and ∠Ts2). To compensate for the fact that the athlete was not centered in the image, the number of pixels the athlete’s annotated COM-position was from the intersection point was counted in the vertical (y-axis) and horizontal direction (x-axis), correcting the angle and direction vector of the total stations to the athlete COM-position (figure 10). The pixel-to-angle ratio was performed at all points where neighboring observations from both cameras existed, resulting in 3D- trajectories of the athletes COM-position. The raw positions of the 3D trajectories were filtered with a cubic spline filter and used to calculate the EFH, “pop”, $V_{Parallel}$, horizontal jump distance, drop height, and landing angle in MATLAB.

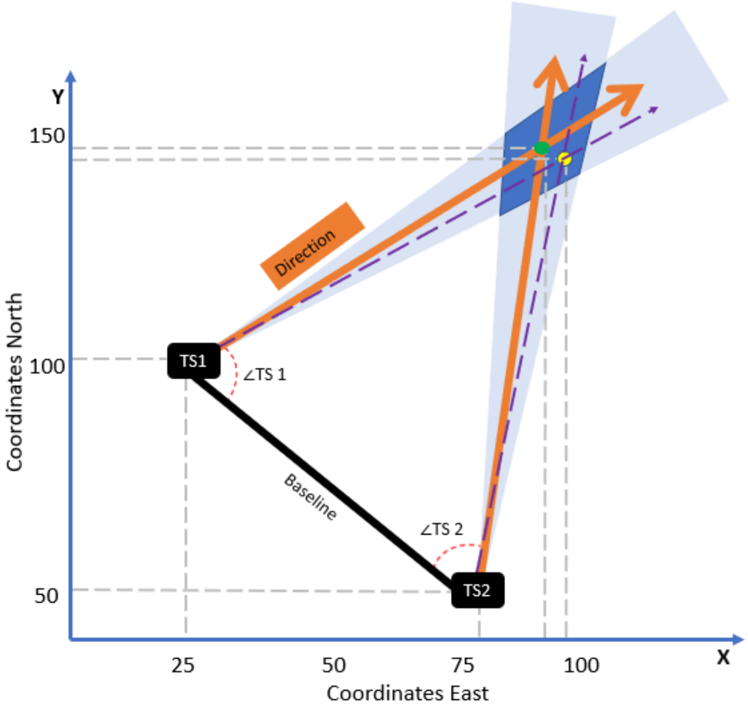

Figure 10: Shows a visual example of the process for the calculation of the athlete's COM using forward intersection, where the athlete (yellow dot) is not centered in the image (dark blue). The figure includes the location of the two total stations (black boxes), the area captured by the total stations (light blue) and the coordinates of their position (dotted grey lines). By using the direction vector of the total stations (orange arrows), their intersection point (green dot) can be found, allowing for forward intersection to locate the athlete's COM-position in 3D space by correcting the angle (∠Ts and ∠Ts2) and direction vector of the total station to the athlete's annotated COM-position (dotted purple arrows).

4.3.4 Course profile

The position data from the snow surface, collected with the Lidar Scanner, was globally aligned with the trajectories using passpoints and the Helmert transformation. A profile was made based on the transformed digital terrain model data. The longitudinal axis of the profile was aligned with the center point coordinates of the jump. Figure 11 shows the shape and dimensions of the jump. In this figure, the jump is divided into four components: approach, take-off (TO), deck, and lading area. The take-off angle ($\angle\theta_T$) was calculated based on the last two meters of the horizontal distance of the kicker. The landing angle ($\angle\,\theta_L$) was calculated over a short distance (4,3 m in the horizontal direction) and was based on the landing points of the athlete’s mean horizontal jumping distance ± Std (24,86m ± 1,67m).

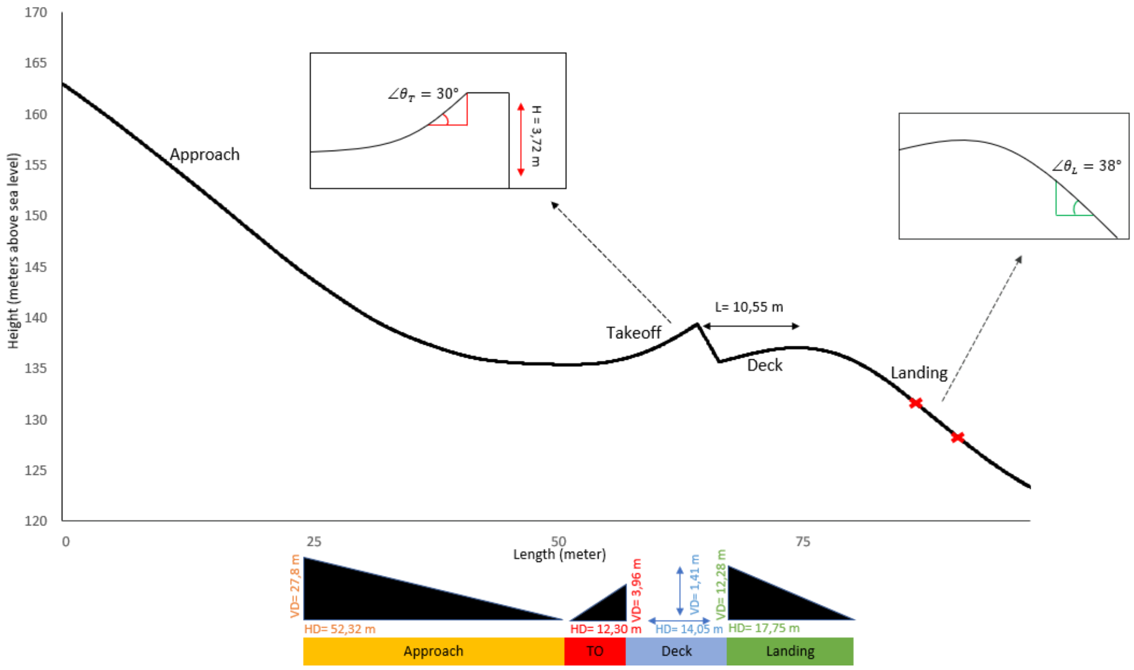

Figure 11: The shape and dimensions of the Big air jump in Mönchengladbach divided into four components; approach (measurements in orange), take-off (red), deck (blue) and landing (green). In addition, the mean landing point ± std is marked in the landing (red cross). HD= horizontal distance of the component. VD= vertical distance of the component. L= horizontal length from take-off lip to highest point of deck (start of landing). H= vertical height from deck to take-off. $\angle\theta_L$= mean angle of landing. $\angle\theta_T$= mean angle of take-off.

4.3.5 Observational assessment of landing quality and rider behavior

Rider variabilities including landing quality, average angular velocity, axial motion, direction of rotation, and rider orientation were extracted using QSecAnalysis and Dartfish 10 ProSuite (Dartfish, Fribourg, Switzerland). Two other observers had already evaluated parts of the data set. The definition of the different variables was done prior to the first evaluation and passed on to the other observers. The two datasets were then compared in Excel to analyze the differences between them before the two observers evaluated the disparity in the data set to reach a common agreement to reduce the inter variability. The intention of having the same definition variables and a collective agreement of the dataset was to enhance the validity and reduce the likelihood of errors due to different interpretations of the variables between the observers.

Landing quality

Due to the low number of injuries registered in a competition it is not plausible to assess injury risk directly through counting the number of injuries. Therefore, landing quality was assessed as a surrogate measure of injury risk. By identifying situations which has an increased likelihood of injury, one can distinguish between situations that have increased and reduced injury risk. However, the association between actual injuries and situations that indicate an increased injury risk is not rigorous. Therefore, when using landing quality as a surrogate measure for injury risk, one accepts a certain level of inaccuracy. In this thesis, the likelihood of injury was evaluated based on events measuring landing quality. In the first perspective, landing quality was assessed based on four different landing characteristics: “Good”, “Slight Unbalanced”, “Touch” and “Fall” (Table 2, Perspective 1).

Table 2: Present three different perspectives of landing quality assessment. Perspective 1 represent landing quality and are divided into four different landing events. Perspective 2 represents landing stability and perspective 3 represents landing balance, where the four events are merged into two categories. Modified illustration from Linløkken (2022, p. 49). Good: The athlete executed a controlled landing. Slight unbalanced: The athlete landed with a minor imbalance but swiftly regained control. Touch: The athlete landed off-balance and had to touch the slope to regain stability. Fall: The athlete fell on the slope.

<table>
<tr><th>Perspective</th><th colspan="4">Events & categories</th></tr>
<tr><td>1</td><td>Good</td><td>Slight Unbalanced</td><td>Touch</td><td>Fall</td></tr>
<tr><td>2</td><td colspan="2">Good landings</td><td colspan="2">Bad landings</td></tr>
<tr><td>3</td><td>Balanced</td><td colspan="3">Unbalanced</td></tr>
</table>

In perspective 2, the four events of landing quality are merged into two categories evaluating the landing stability (“Good” and “Bad” landings), enhancing the statistical power. However, unbalanced landings are often associated with fall situations, and “slight unbalanced” landings can therefore be considered as an event that increases the risk of injury. Hence, landing balance is included as a third perspective of landing quality, dividing events into two categories; “Balanced” and “Unbalanced”.

In this thesis, the injury risk was investigated according to the three different perspectives of landing quality described above. Fall (perspective 1) situations represented the most accurate classification regarding injury risk but contained few cases (mainly in ski), resulting in low statistical power. Perspective 3 (landing balance) had a higher number of cases, which led to increased statistical power but is the least accurate measure. Landing stability (perspective 2) had a combination of moderate measurement accuracy and statistical power and was for this reason used as the primary outcome measure in the regression analysis.

Average Angular velocity

Average angular velocity (ωavg) was calculated based on the equation:

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

Where $\Delta\theta$ is the angular displacement (degrees rotated) between the take-off (θ_0) and the landing (θ_1). The angular displacement was calculated by counting the number of rotations of the athletes in the video footage and was always zero at take-off. The angular displacement was divided on the difference in time (Δt) between the take-off (t_0) and the landing (t_1) and represent the athlete’s airtime. The take-off time (t_0) was defined as the last moment where the athlete’s equipment touched the kicker, while the landing time (t_1) was defined as the first moment where the athlete’s equipment was in contact with the landing surface. The angular velocity of the athlete changes throughout the maneuver which is complex to calculate. Therefore, in this thesis, variations in angular velocity throughout the maneuver were neglected, and calculations were conducted based on an assumed average angular velocity for the maneuver. Hence, the variable is referred to as average angular velocity (ω_{avg}).

The airtime differed between observers since it was difficult to see the exact point of take-off and landing due to low contrast in the video footage. Comparison between the observers resulted in an absolute mean difference in airtime of 0,0247s ± 0,0329.

Therefore, the two observers examined together all the outliers with an absolute mean difference in airtime of less than 0,04s (n:41 videos). After agreeing on the take-off and landing moment on these outliers, we got an absolute mean difference in airtime of 0,0149s ± 0,0150. Thereafter, we calculated the average airtime between the two observers in each video(run). This average airtime between the two observers was utilized in this thesis and used to compute the ω_{avg}, increasing the validity of the results.

Axial motions

The maneuvers of the athletes were categorized into various tricks, which in turn were divided into monoaxial or multiaxial. Monoaxial maneuvers was defined as rotations performed around one axis, while multiaxial manoeuvres were defined as rotations performed around two or several axes. Cork, Bio, Rodeo, Misty, and Underflip were categorized as multiaxial maneuvers. Straight and Flips were categorized as monoaxial maneuvers. Appendix 1 provides additional details regarding the explanation of the different maneuvers.

Direction of rotation

In snowboarding, the identification of rotational direction was derived from observation, classified into two categories; frontside and backside rotation.

Rider orientation

By observing the orientation of the skiers at take-off, one could establish if the athlete was riding normal or switch. In snowboard, which foot the athletes had in front at take-off was identified and then compared to their preferred foot, which was collected prior to the competition. With this information, it was possible to determine if the athletes were riding regular or goofy.

4.4 Data analysis

4.4.1 Physical data analysis

The data was analyzed through QDaedalus and MATLAB with the purpose to reconstruct the annotations in 2D, into 3D trajectories for each run. Further, MATLAB script were used calculate parameters to answer the research question. The main parameters of interest were the component velocity perpendicular to the landing, which was used to estimate EFH. The take-off velocity parallel to the surface ($V_{Parallel}$), the "pop" and the mean horizontal jump distance were also important factors to determine the flight trajectory of the athletes. Additionally, drop height and landing angle were calculated to provide further insight into the landing dynamics (figure 12). As a result of computational constraints, a portion of the physical data was unable to be retrieved, leaving us with access to the physical data of only one female skier. Furthermore, physical data of two athletes were excluded from the dataset due to the presence of unrealistic values, such as a negative horizontal jump distance and an extremely low EFH value, indicating possible calculation errors.

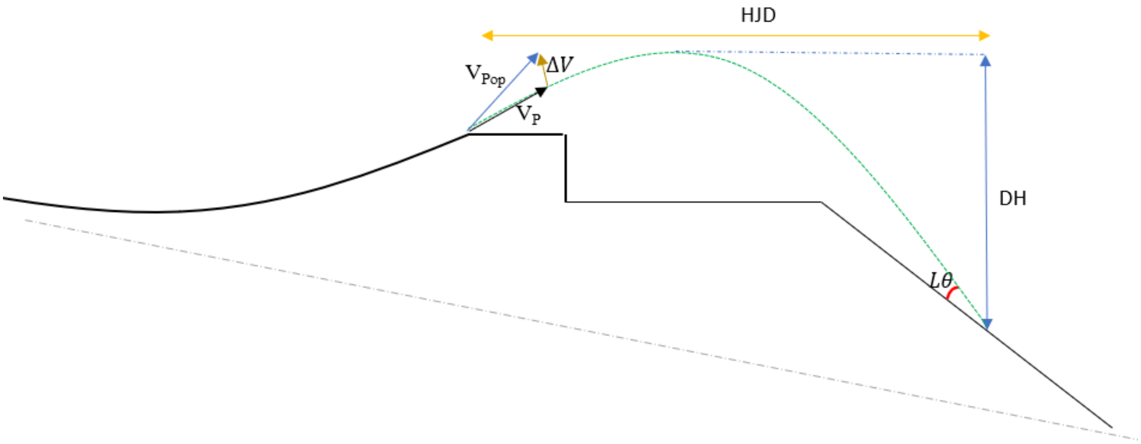

Figure 12: Illustration of a step-down jump design, the flight trajectory of the athlete (green dashed line), and the physical parameters of interest obtained through calculations in MATLAB: take-off velocity parallel to the surface (V_P), the change in jump trajectory (ΔV) due to the pop at take-off resulting in a change in the take-off velocity in both magnitude and direction (V_{Pop}). Furthermore, the illustration presents the horizontal jump distance (HJD), which is calculated from the take-off lip to the landing point. The drop height (DH) is measured as the vertical disparity from the athlete's maximum height while airborne to the landing point. The landing angle ($L\theta$) is determined as the angle difference between the trajectory angle and the angle of the landing slope.

4.4.2 Equivalent fall height

The fall height (h) of the athlete is related to the velocity (v) at impact through the equation h= v^2/2g, where g is the gravitational acceleration. However, when jumping and landing on a slope, only the velocity component perpendicular to the landing surface ($v_\perp$) must be brought to zero, given by the equation: h= $v_\perp^2$/2g. The component of the landing velocity perpendicular to the landing surface is the product of the landing velocity of the athlete (V_A) and the athlete's flight path angle (θ_A) relative to the landing slope angle (θ_L). This equation is given by $V_\perp = V_A sin\,(\theta_A - \theta_L)$ (Hubbard &

Swedberg, 2012, p. 3; McNeil et al., 2012, p. 6; Swedberg & Hubbard, 2012, p. 122). Thus, the expression for EFH is:

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

The athlete's landing velocities were calculated based on position- time derivation over four points of the entire trajectory, using a central difference method. The landing point was defined as the point where the COM trajectory of the athlete and an imaginary plane placed 0,9 meters above ground intersected.

4.4.3 Data analysis of the observational assessment of landing quality and rider behavior

The complexity of maneuvers and landing stability is described by rider behavior. The difficulty of a maneuver is determined based on the ω_{avg} and the axial motion of the maneuver. Rider orientation during landing and take-off was also considered to influence the complexity. It was anticipated that increased complexity would reduce landing stability and increase the likelihood of falling. The degree of injury risk was assessed using landing stability as a surrogate measure.

Descriptive analysis

First, the descriptive data were analyzed to investigate the differences between group properties, EFH, landing quality, and the rider behavioral factors between and within groups. The descriptive data collected in this thesis was also compared to a previous study conducted in a Slopestyle competition in Seiser Alm, to investigate differences related to jump design and competition formats. Male and female athletes have different requirements for performance and compete in separate competitions, thus it was natural to separate them in the analysis.

Determination of potential injury risk factors

Secondly, the aim was to link EFH with rider behavior and examine the relationship between different variables and landing stability. The analysis was conducted for all snowboarders combined, as well as for male skiers and male snowboarders separately. Analyzing the entire skiing group would lack interest since it consists of only one female skier. In this case, the analysis would yield similar results as if it solely focused on male skiers. In snowboarding, the analysis was conducted both with and without female athletes to facilitate the exploration of connections between skiing and snowboarding. The analysis was controlled for sex, ensuring that any observed differences in the results were not solely attributed to sex. Furthermore, male and female athletes have different requirements for performance and compete in separate competitions, thus it was natural to separate them in the analysis.

Variable predictors of EFH

In the final analysis, the aim was to examine the variables that could serve as predictors of EFH. The analysis was conducted for all snowboarders combined, as well as for male skiers and male snowboarders separately. The variables considered in the analyses included $V_{Parallel}$, pop, drop height, and landing angle.¨

4.5 Statistics

The data analysis, compromising descriptive statistics, logistic regression, and linear regression were conducted using IBM SPSS. Table 3 presents an overview of the statistical methods used to investigate group differences in the descriptive data.

Table 3: *An overview of the variables that were tested and their corresponding statistical tests used to analyze group differences. Additional rider variabilities represent rider orientation during take-off and landing and rotational direction.*

Variables	Chi square	Independent sample t-test	Mann Whitney U-test	One Way ANOVA with Post-hoc Bonferroni	Kruskal Wallis 1-way ANOVA
Mass, height, and BMI			Between sex, and between equipment		Between subgroups
Landing quality	All comparisons				
EFH		Between	Between subgroups		

Variables	Chi square	Independent sample t-test	Mann Whitney U-test	One Way ANOVA with Post-hoc Bonferroni	Kruskal Wallis 1-way ANOVA
		subgroups (SB)	(male)		
Pop		All comparisons			
$V_{Parallel}$		All comparisons			
Drop height			All comparisons		
Landing angle		All comparisons			
Horizontal jump distance		Between subgroups (SB)	Between subgroups (male)		
Angular velocity		Between sex and between equipment		Between subgroups	
Airtime		Between sex and between equipment		Between subgroups	
Axial motion	All comparisons				
Additional rider variabilities	All comparisons				

Determination of potential injury risk factors

To explore the factors influencing landing stability, a logistic regression analysis was performed. In this analysis, landing stability was considered the dependent variable, with a code of 0 assigned to indicate good landing stability and 1 to indicate bad landing stability. The model's reference value was set as having good landing stability. The analysis was performed for snowboarders as a whole group and separately for male skiers and male snowboarders. Continuous variables such as EFH and ω_{avg} were included in the model, along with dichotomous variables such as rider orientation during landing, axial motions, and rotational direction. The reference value of the independent variables was regular landing, multiaxial maneuvers, and BS rotation (table 4). In all three analyses, the interaction effect of ω_{avg} by axis was examined. Additionally, the models were assessed for multicollinearity and other interaction effects between variables.

Table 4: Overview of the variables included in the logistic regression.

Variables	**Type**	**Coding**	
		0	**1**
Landing stability	Categorical	Good	Bad
Axial motions*	Categorical	Multiaxial	Monoaxial
Landing orientation	Categorical	Regular	Switch
Rotational direction*	Categorical	Backside	Frontside
EFH	Continuous	n/a	
Angular velocity	Continuous	n/a	

*= only investigated for snowboarders

Variable predictors of EFH

A linear regression analysis were performed to investigate the variable predictors of EFH, with EFH as the dependent variable. The analysis was conducted for snowboarders as a whole group and separately for male snowboarders and male skiers.

As physical data was available for only one female skier, the model was restricted to male skiers to maintain the specificity and prevent the impact of a single female athlete on the results. The model included continuous variables such as $V_{Parallel}$, pop, drop height, and landing angle. In the initial analysis, the focus was on exploring the predictive relationship of $V_{Parallel}$ and pop concerning EFH. Subsequently, to further enhance the examination of EFH prediction variables and develop a more comprehensive explanatory model, drop height and landing angle were included as additional independent factors in the analysis. To ensure accuracy, all models were evaluated for multicollinearity, outliers, and normality of residuals.

4.6 Ethical considerations

This thesis is part of a bigger ongoing project spanning over several years and follows ethical guidelines. The ethical guidelines have already been approved by the ethical committee at the Norwegian School of Sports Science and the Norwegian Centre for Research Data. The application IDs are:

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

5. Results

5.1 Anthropometrics

Table 5 shows comparisons of anthropometrics between sex, equipment, and subgroups, with missing data on two female snowboarders.

Table 5: Shows the mean value and standard deviation of mass and height for different groups. Comparisons are done between sex, equipment, and subgroups.

Group	Mass (kg)	Height (cm)
Sex		
Male athletes	84,19 ± 8,2**	178,16 ± 7,26**
Female athletes	69,16 ± 6,3**	165,09 ± 5,26**
Equipment		
Freeski	80,24 ± 11,8	173,26 ± 8,67
Snowboard	78,46 ± 9,5	173,96 ± 9,32
Subgroups		
Male skiers	87,23 ± 9,3 ^{ab}	177,89 ± 7,34 ^{a}
Female skiers	68,73 ± 3,6 ^{a}	165,62 ± 4,07 ^{a}
Male SB	82,73 ± 7,1 ^{ab}	178,30 ± 7,26 ^{a}
Female SB	69,42 ± 7,6 ^{a}	164,77 ± 5,89 ^{a}

^{a}= Significant difference p<0,001 (Kruskal-Wallis) between sex within equipment, ^{b}= significant difference p<0,05 (Kruskal-Wallis) between equipment within sex. *=Significant difference between populations p<0,05, **=significant difference between populations p<0,001, SB= Snowboard.

Male athletes exhibited a significantly higher mass and height compared to their female counterparts, both within subgroups and across the entire sample (p<0,001). No difference was observed in mass or height between freeski and snowboard. Male skiers had a significantly higher mass (p<0,05) compared to male snowboarders, while there was no difference in height. Female snowboarders and female skiers did not exhibit any difference in mass or height.

5.2 Landing quality

An overview of the incidence of falls, bad landing stability, and unbalanced landings in male and female athletes, as well as in skiing and snowboarding, is presented in Table 6. There was no significant difference between male and female athletes in landing quality. Snowboarders had a significantly higher incidence of falls, bad landing stability (p<0,001) and unbalanced landings (p<0,05) compared to skiers.

Table 6: An overview of the percentage of falls, bad landing stability, and unbalanced landings in male athletes, female athletes, skiers, and snowboarders. Comparisons are done between male and female athletes and between skiers and snowboarders. The fall incidence is included in bad landing stability, while bad landing stability is included in unbalanced landings.

Group	**Fall incidence**	**Bad landing stability**	**Unbalanced landings**
Sex			
Male athletes	30,9%	47,3%	62,2%
Female athletes	33,3%	47,5%	60,6%
Equipment			
Freeski	15,3%**	26,5%**	49%*
Snowboard	40,2%**	58,2%**	68,3%*

*=Statistical difference between groups p<0,05, **=Statistical difference between groups p<0,001.

SB=Snowboard

Figure 13 illustrates that male snowboarders had a significantly higher incidence of falls, bad landings and unbalanced landings compared to male skiers (p<0,001). A higher incidence of falls was observed in female snowboarders in comparison to female skiers (p<0,05), while no difference was found in bad landing or unbalanced landings. Female skiers had a higher incidence of bad landings compared to male skiers (p<0,05), with no difference in falls or unbalanced landings. There was no difference between female and male snowboarders.

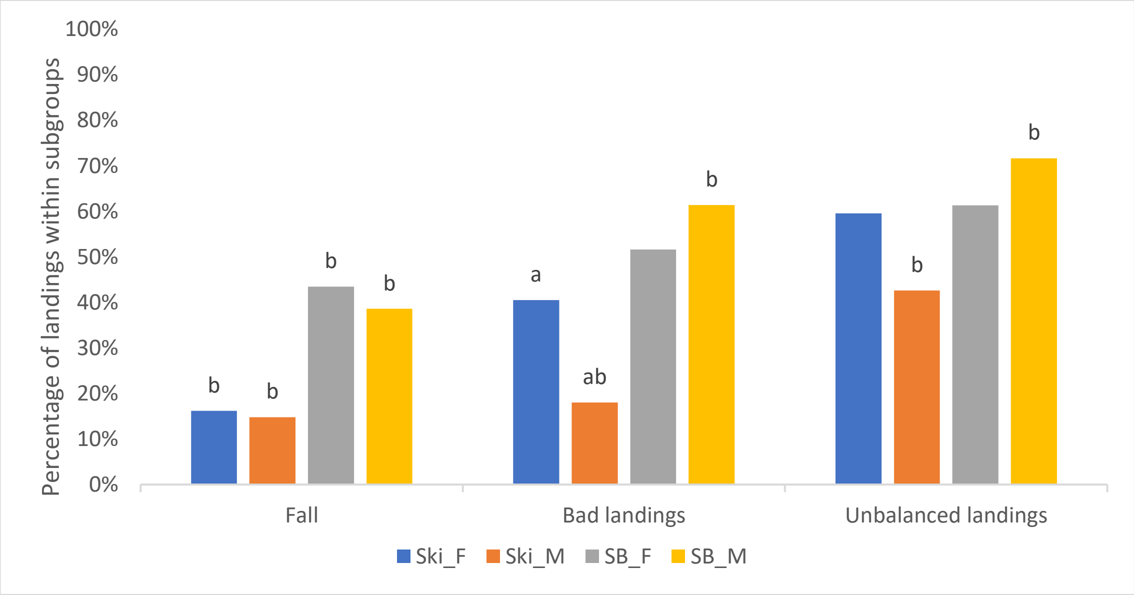

Figure 13: Shows the percentage of falls, bad landings and unbalanced landings within the 4 different groups; Ski_F (female skiers), Ski_M (male skiers), SB_F (female snowboarders) and SB_M (male snowboarders).
a= Difference between sex within equipment, p<0,05.
b= Difference between equipment within sex, p<0,05

5.3 Rider behavior

As shown in Table 7, male athletes in both freeski and snowboarding had significantly higher values of airtime, ω_{avg}, and axial motion compared to female athletes (p<0,001). There was no significant difference between freeski and snowboarding. Male skiers had higher values of airtime (p<0,001) and axial motion (p<0,05) compared to male snowboarders, with no difference in ω_{avg}. Female skiers had significantly higher values of ω_{avg} compared to female snowboarders (p<0,001), while no difference was observed in airtime or axial motion.

Table 7: Shows rider variabilities that impact the complexity of a mauver. Mean values and standard deviation are presented for airtime and ω_{avg}. Axial motion is presented as the percentage of maneuvers within the population that were executed multiaxial. Comparisons are done between sex, equipment, and subgroups.

Group	**Airtime (s)**	**ω_{avg} (°/s)**	**Axial motion (%)**
Sex			
Male athletes	2,29 ± 0,12**	527,84 ± 66**	92**
Female athletes	2,05 ± 0,12**	324,98 ± 83**	41,4**
Equipment			
Freeski	2,22 ± 0,21	471,54 ± 108	73,5
Snowboard	2,20 ± 0,14	450,77 ± 126	75,1
Subgroups			
Male skiers	2,35 ± 0,13 [ab]	539,07 ± 63 [a]	98,4 [ac]
Female skiers	2,01 ± 0,14 [a]	360,20 ± 66 [ab]	32,4 [a]
Male SB	2,26 ± 0,11 [ab]	522,44 ± 67 [a]	89,0 [ac]
Female SB	2,07 ± 0,11 [a]	303,97 ± 86 [ab]	46,8 [a]

[a]= Significant difference p<0,001 (Bonferroni) between sex within equipment, [b]= significant difference p<0,001 (Bonferroni) between equipment within sex, [c]= significant difference p<0,05 between equipment within sex. *=Significant difference between populations p<0,05, **=significant difference between populations p<0,001. SB= Snowboard.

Furthermore, Table 8 shows rider behavior factors regarding orientation during take-off and landing, in addition to the direction of rotation in snowboarders. Male skiers had a higher proportion of switch rider orientation during take-off compared to female skiers

($p<0,05$), with no difference in rider orientation during landing. There was no difference in rider orientation during take-off, rider orientation during landing, or the direction of rotation between male and female snowboarders.

Table 8: An overview of rider orientation during take-off and landing in freeski and snowboard, in addition to the direction of rotation in snowboard. Rider orientation is presented as the percentage within the population that was riding switch, while direction of rotation is the percentage within the population that performed a frontside rotation. Comparisons are done between male and female athletes within the discipline. Discipline comparison was not conducted, because riding switch requires different techniques across disciplines.

Groups	**Freeski**		**Snowboard**	
	Male	**Female**	**Male**	**Female**
Rider orientation at Take-off				
Switch (%)	50,8*	29,7*	37,8	24,2
Rider orientation at Landing				
Switch (%)	49,2	64,9	26	17,7
Direction of rotation (SB)				
Frontside rotation (%)	-	-	39,4	33,9

*=Significant difference between male and female athletes within discipline $p<0,05$. SB=Snowboard.

5.4 Physical variables of jump trajectory

Table 9 shows the mean value of different physical variables for male skiers, male snowboarders, and female snowboarders. As a result of computational limitations, certain physical data was lost during the calculation of variables. Consequently, only the physical variables for a single female skier could be extracted, making it impractical to provide the mean of the physical values for this group. Male snowboarders had higher values of both EFH, jump distance, drop height, landing angle ($p<0,001$), pop, and

$V_{Parallel}$ ($p<0,05$) compared to their female counterparts. Male skiers had higher values of jump distance, $V_{Parallel}$, and drop height compared to male snowboarders ($p<0,001$), while male snowboarders had higher values of landing angle compared to male skiers ($p<0,05$), with no difference in EFH or pop.

Table 9: Overview of the mean value and standard deviation of different physical variables; equivalent fall height (EFH), pop, horizontal jump distance (jump distance), velocity parallel to the surface at take-off ($V_{Parallel}$), the vertical height from the highest point to the landing (drop height) and the landing angle within male skiers, male snowboarders, and female snowboarders. The comparison was done between male skiers and male snowboarders and between male and female snowboarders.

Variable	Ski Male	SB Male	SB Female
EFH (m)	1,69 ± 0,55	1,48 ± 0,23[a]	1,20 ± 0,17[a]
Pop (m/s)	0,86 ± 0,61	1,04 ± 0,59[a]	0,73 ± 0,55[a]
Jump distance (m)	25,30 ± 1,59[b]	22,25 ± 1,54[ab]	20,80 ± 1,51[a]
$V_{Parallel}$ (m/s)	13,53 ± 0,56[b]	12,75 ± 0,43[ab]	12,42 ± 0,51[a]
Drop height (m)	13,06 ± 1,29[b]	10,94 ± 1,40[ab]	9,44 ± 1,21[a]
Landing angle (°)	17,67 ± 1,97[b]	18,54 ± 1,76[ab]	17,50 ± 2,18[a]

[a]= Significant difference $p<0,05$ between sex within equipment, [b]= significant difference $p<0,05$ between equipment within sex. SB= Snowboard.

5.5 Determination of potential injury risk factors

Freeski male

Table 10 shows that neither EFH, ω_{avg}, or rider orientation during landing in freeski were significant predictors for landing outcome. The axial motion was not incorporated into the model as all subjects performed a multiaxial maneuver. It was only possible to obtain physical data on one female athlete. To ensure the model's specificity and eliminate any potential bias towards sex differences in the model, only male ski athletes were included. The model underwent testing for additional interaction effects and multicollinearity between variables, which were found to be insignificant. Consequently, this model is employed to demonstrate the parameters that have undergone testing, revealing no significant results.

Table 10: Variables in the model were tested with logistic regression to evaluate if EFH, ωavg, or rider orientation during landing could influence the landing stability for male skiers. Landing stability: Good landings = 0 / Bad landings = 1. The odds ratio (OR) determines the likelihood of a bad landing outcome in relation to the reference value of the independent variable. The independent variable's reference value is coded as 0, and the test variable is coded as 1. If OR= 1, the probability of a bad landing outcome is the same for both the reference and test variable. If OR > 1, the test variable has a higher likelihood of a bad landing outcome than the reference variable. If OR < 1, the test variable has a lower probability of a bad landing outcome than the reference variable.

Variable in equation	**Beta coefficient**	**Odds ratio (OR)**	**Lower 95%CI**	**Upper 95%CI**
Constant	-2,579	0,076		
EFH	-0,368	0,692	0,040	11,854
ω_{avg}	0,001	1,001	0,988	1,014
Rider orientation during landing	1,321	3,745	0,342	41,059

*= p<0,05, EFH= Equivalent fall height, ω_{avg}= average angular velocity, Rider orientation during landing: Regular orientation during landing = 0 / Switch orientation during landing = 1, CI= Confidence interval. Model x^2 (3) = 1,441, p=0,696.

Snowboard male

Table 11 displays identical variables to those in Table 7, but for male snowboarders only. The model was evaluated for multicollinearity and additional interaction effects among variables, which were found to be insignificant. None of the variables demonstrated significant predictor power for landing stability.

Table 11: *Variables in the model were tested with logistic regression to evaluate if EFH, ωavg, axial motions, rotational direction, or rider orientation during landing could influence the landing stability for male snowboarders. Landing stability: Good landings = 0 / Bad landings = 1. The odds ratio (OR) determines the likelihood of a bad landing outcome in relation to the reference value of the independent variable. The independent variable's reference value is coded as 0, and the test variable is coded as 1. If OR= 1, the probability of a bad landing outcome is the same for both the reference and test variable. If OR > 1, the test variable has a higher likelihood of a bad landing outcome than the reference variable. If OR < 1, the test variable has a lower probability of a bad landing outcome than the reference variable.*

Variable in equation	**Beta coefficient**	**Odds ratio (OR)**	**Lower 95%CI**	**Upper 95%CI**
Constant	2,781	16,131		
EFH	-0,399	0,671	0,039	11,511
ω_{avg}	-0,004	0,996	0,985	1,007
Axial motions	-7,432	0,001	0,000	517,195
Rotational direction	0,832	2,298	0,648	8,146
Rider orientation during landing	0,619	1,857	0,475	7,264
Angular velocity by axis	0,016	1,016	0,987	1,046

*= $p<0{,}05$, EFH= Equivalent fall height, ω_{avg}= average angular velocity, Axial motions: Multiaxial maneuvers = 0 / Monoaxial maneuvers = 1 , Rotational direction: Backside rotation = 0 / Frontside rotation = 1, Rider orientation during landing: Regular orientation during landing = 0 / Switch orientation during landing = 1, CI= Confidence interval. Model x^2 (6) = 3,982, p=0,679.

Snowboard

Table 12 shows that neither EFH, ω_{avg}, axial motions, rotational direction, rider orientation during landing, or the interaction effect between ω_{avg} and axial motions in snowboard were significant predictors for landing outcome. Sex was not a main predictor for landing outcome and was thus excluded from the model. The model underwent testing for multicollinearity and additional interaction effects between variables, which were found to be insignificant. None of the variables demonstrated significant predictor power for landing stability.

Table 12: Variables in the model were tested with logistic regression to evaluate if EFH, ω_{avg}, axial motions, rotational direction, or rider orientation during landing could influence the landing stability for snowboarders. Landing stability: Good landings = 0 / Bad landings = 1. The odds ratio (OR) determines the likelihood of a bad landing outcome in relation to the reference value of the independent variable. The independent variable's reference value is coded as 0, and the test variable is coded as 1. If OR= 1, the probability of a bad landing outcome is the same for both the reference and test variable. If OR > 1, the test variable has a higher likelihood of a bad landing outcome than the reference variable. If OR < 1, the test variable has a lower probability of a bad landing outcome than the reference variable.

Variable in equation	**Beta coefficient**	**Odds ratio (OR)**	**Lower 95%CI**	**Upper 95%CI**
Constant	0,664	1,943		
EFH	-0,188	0,829	0,134	5,122
ω_{avg}	0,000	1,000	0,995	1,005
Axial motions	-0,813	0,443	0,016	12,475
Rotational direction	0,306	1,358	0,525	3,515
Rider orientation during landing	0,578	1,782	0,599	5,303
Angular velocity by axis	0,002	1,002	0,994	1,011

*= p<0,05, EFH= Equivalent fall height, ω_{avg}= average angular velocity, Axial motions: Multiaxial maneuvers = 0 / Monoaxial maneuvers = 1 , Rotational direction: Backside rotation = 0 / Frontside rotation = 1, Rider orientation during landing: Regular orientation during landing = 0 / Switch orientation during landing = 1, CI= Confidence interval. Model x^2 (6) = 2,055, p=0,915.

5.6 Predictors of equivalent fall height

Freeski male

The linear regression analysis, revealed that the model presented in Table 13 was significant (p<0,05) in predicting the EFH. $V_{Parallel}$ and pop were able to explain 29,2% (r^2 = 0,292) of the observed variation in EFH. However, it was only $V_{Parallel}$ that was a significant predictor of EFH (p<0,05).

Table 13: Variables in the model were tested with linear regression to evaluate whether $V_{Parallel}$ and pop could predict EFH in male skiers. The beta-values were used to indicate the change in the predicted EFH for each one-unit increase in the independent variables, along with their corresponding 95% confidence intervals (lower and upper 95%CI) and p-value.

Independent variables	Beta coefficients (standardized)	Lower 95%CI	Upper 95%CI	p-value
Constant	-5,858	-10,496	-1,219	0,015*
$V_{Parallel}$ (m/s)	0,566	0,216	0,888	0,002*
Pop (m/s)	0,111	-0,208	0,406	0,514

*= Coefficient (beta-value) of independent factor significantly different from 0 (p<0,05)

One-way ANOVA = p<0,05

After incorporating drop height and landing angle in the model (table 14), it became evident that the model exhibited significant predictive ability for EFH (p<0,001) and accounted for 90,0 % ($r^2 = 0{,}900$) of the observed variation in EFH. Drop height and landing angle were found to be significant predictors of EFH (p<0,001), such that an increase in these variables would increase EFH corresponding to the values of the beta-coefficients. $V_{Parallel}$ and pop were not found to be significant predictors of the EFH outcome. However, the model did not contain normally distributed residuals, likely due to the presence of two high values of EFH. Nonetheless, the same analyses (tables 13 & 14) were performed after removing the two high EFH values, resulting in normally distributed residuals. In the first model, neither $V_{Parallel}$ nor pop demonstrated significant predictive ability for EFH, leading to an overall non-significant model. However, in the final model, the same variables remained significant predictors of EFH with a similar level of explanatory power (Appendix 2). Consequently, the model incorporating all values of EFH was ultimately chosen for analysis. However, caution is needed when interpreting the beta-coefficient, as the assumption of linear regression is not present.

Table 14: Variables in the model were tested with linear regression to evaluate whether $V_{Parallel}$, pop, drop height, and landing angle could predict EFH in male skiers. The beta-values were used to indicate the change in the predicted EFH for each one-unit increase in the independent variables, along with their corresponding 95% confidence intervals (lower and upper 95%CI) and p-value.

Independent variables	Beta-coefficients (standardized)	Lower 95%CI	Upper 95%CI	p-value
Constant	-3,788	-5,670	-1,906	<0,001**
$V_{Parallel}$ (m/s)	0,019	-0,147	0,184	0,882
Pop (m/s)	-0,010	-0,131	0,114	0,884
Drop height (m)	0,509	0,120	0,312	<0,001**
Landing angle (°)	0,494	0,082	0,191	<0,001**

**= Coefficient (beta-value) of independent factor significantly different from 0 (p<0,001)

One-way ANOVA = p<0,001

Snowboard

The model presented in Table 15 exhibited significant predictive ability for EFH ($p<0,05$), where $V_{Parallel}$ and pop explained 8,9% ($r^2=0,089$) of the observed variation in EFH. Contrary to what was found in skiers, it was only pop that was a significant predictor of EFH ($p<0,05$) in snowboarders. An increase in pop would result in an increase of EFH corresponding to the beta-coefficients.

Table 15: Variables in the model were tested with linear regression to evaluate whether $V_{Parallel}$ and pop could predict EFH in snowboarders. The beta-values were used to indicate the change in the predicted EFH for each one-unit increase in the independent variables, along with their corresponding 95% confidence intervals (lower and upper 95%CI) and p-value.

Independent variables	Beta coefficients (standardized)	Lower 95%CI	Upper 95%CI	p-value
Constant	0,627	-0,658	1,912	0,335
$V_{Parallel}$ (m/s)	0,103	-0,050	0,154	0,312
Pop (m/s)	0,272	0,029	0,195	0,009*

*= Coefficient (beta-value) of independent factor significantly different from 0 (p<0,05).

One-way ANOVA = p<0,05

After incorporating drop height and landing angle into the model (table 16), the model's explanatory power increased to 84,6 % (r^2=0,846) and it demonstrated significant predictive ability for EFH (p<0,001). Both drop height, landing angle (p<0,001), and pop (p<0,05) were found to be significant predictors of EFH, where an increase in either would result in a change in the EFH corresponding to the beta-coefficients. The prerequisites for linear regression were met, as indicated by normally distributed residuals and the absence of multicollinearity.

Table 16: Variables in the model was tested with linear regression to evaluate whether $V_{Parallel}$, pop, drop height and landing angle could predict EFH in snowboarders. The beta-values were used to indicate the change in the predicted EFH for each one-unit increase in the independent variables, along with their corresponding 95% confidence intervals (lower and upper 95%CI) and p-value.

Independent variables	**Beta-coefficients (standardized)**	**Lower 95%CI**	**Upper 95%CI**	**p-value**
Constant	-1,130	-1,750	-0,510	<0,001**
$V_{Parallel}$ (m/s)	-0,058	-0,078	0,019	0,225
Pop (m/s)	-0,098	-0,078	-0,003	0,036*
Drop height (m)	0,697	0,097	0,129	<0,001**
Landing angle (°)	0,767	0,085	0,108	<0,001**

*= Coefficient (beta-value) of independent factor significantly different from 0 (p<0,05)

**= Coefficient (beta-value) of independent factor significantly different from 0 (p<0,001)

One-way ANOVA = p<0,001

6. Discussion

6.1 Group comparisons

According to the findings on body composition, male athletes have larger mass in comparison to their female counterparts in both freeski and snowboarding (table 5). When designing a jump, one should consider the mass differences between male and female athletes as both sexes use the same course, and this difference in mass may have an impact on the take-off velocity (Wolfsperger et al., 2021, p. 1085). Further, studies show that men have a greater lean mass than women (Schorr et al., 2018, p. 4). A higher muscle-to-mass ratio in male athletes and their superior leg strength may facilitate generating more momentum and altering their flight trajectory to a greater extent compared to female athletes. This is supported by the findings in this study, where male snowboarders have larger values of both pop, $V_{Parallel}$ (table 9), and ω_{avg} (table 7) than female snowboarders, which is consistent with the findings of Hoholm (2022, p. 72) and Linløkken (2022, pp. 60-61) in Slopestyle. Unlike Hoholm (2022, p. 72) findings, in this study male snowboarders had a larger horizontal jump distance compared to their female counterparts. This further highlights the significance of considering sex differences when designing jumps. In addition, the superior muscle-to-mass ratio in male athletes may lead to an advantage in stopping their momentum and resisting the impact upon landing, which may result in better landing stability. In this thesis, the analysis did not identify sex as a primary predictor for landing stability neither for freeski nor snowboard. In contrast, Linløkken (2022, p. 66) identified sex as a primary predictor of landing stability in freeski. It is essential to emphasize that the disparity in landing stability between sexes may not solely be attributed to sex itself, but rather to differences in mass and muscle strength typically associated with sex and potentially also motor control aspects. Consequently, when designing jumps, it is crucial to consider accommodating the range of take-off velocities of athletes, encompassing both the minimum and maximum values, to optimize landing performance and ensure the safety of all athletes.

6.2 Landing stability

This thesis categorized landing quality into three distinct categories; individuals who fell, those who had bad landings (fall and touch), and those who had unbalanced landings (fall, touch, and slight unbalanced). Out of these three categories, landing stability (bad & good landings) was selected as the surrogate measure for the risk to get injured. As previously discussed in the theory section, the surrogate measure is only considered valid if it is closely linked to the risk of injury (Johnsson et al., 2018, p. 766; Kröll et al., 2017, p. 1645). Studies indicate that the primary mechanism of injury is associated with the loss of control and falling (Bakken et al., 2011, p. 1317; Brooks et al., 2010, p. 120; Moffat et al., 2009, p. 259; Randjelovic et al., 2014, p. 32). Consequently, falling is the most reliable surrogate measure to evaluate the risk of injury. Nonetheless, this category has a small number of cases, particularly among skiers. As a result, bad landings are used as a surrogate measure to improve the statistical power accepting a higher level of uncertainty for the link between predictor of injury and real injuries. However, this approach may result in an overestimation of the true injury risk since not all instances of bad landings necessarily lead to injury. Hence, the findings of this study cannot be directly compared to research that has investigated the actual occurrence of injuries. However, the findings can be compared to those of Linløkken (2022) and, to a certain extent, to the research by Kurpiers et al. (2017), who examined the relationship between rider behavior and falls in recreational snowboard athletes. To the best of our knowledge, this study is the first of its kind to examine landing stability related to rider behavior and EFH among elite athletes in a Big air event and hence a first attempt to predict injury risk through surrogate measure of the true risk.

There was no significant difference in landing outcomes between male and female athletes in any of the three perspectives (table 6). Similarly, no sex differences were observed in subgroups, except for bad landings in freeski, where female skiers had a higher incidence of bad landings than male skiers (figure 13). This suggests similar results to several studies, including those conducted by Goulet et al. (2007), Linløkken (2022), and Major et al. (2014), all of which found no difference in landing quality or injury risk between sex. Some similarities can be drawn to the results of Soligard et al. (2015), who found no sex differences regarding injury risk in snowboarding but did observe a discrepancy among skiers. In contrast, these results are distinct from the findings of Palmer et al. (2021) and Russell et al. (2014), who identified a significant sex difference in their studies. Nevertheless, making such comparisons is challenging because most of the studies mentioned above have examined the actual injury rate, whereas this project has relied on bad landings as a surrogate measure. Additionally, there exists a significant difference in skill level and jump design across the different studies. Consequently, the injury rate among male and female athletes may considerably differ depending on the discipline, jump design, and skill level.

Snowboarders had a considerably greater incidence of falls, bad landings, and unbalanced landings compared to skiers (table 6). These findings are in contrast with other literature that has reported a similar risk of injury between disciplines, with skiers having a tendency for a slightly higher risk of injury (Carús & Escorihuela, 2016a; Carús & Escorihuela, 2016b; Russell et al., 2013; Russell et al., 2014). However, comparing these studies across disciplines is challenging as they were conducted on different individuals, at various times, for different durations, and in different TP which may have varying degrees of difficulty. Nevertheless, in a Slopestyle event where athletes competed on the same course, Steffen et al. (2017, p. 31) discovered a similar injury risk between freeski and snowboard in a Slopestyle event. However, it should be noted that their study consisted of youth athletes, who may have had a lower skill level compared to the athletes in our study, which could account for the differing results.

Moreover, male snowboarders had a greater incidence of bad landing outcomes across all three-landing quality perspectives when compared to male skiers (figure 13). Additionally, female snowboarders demonstrated a higher incidence of falls compared to female skiers, while no significant difference was observed in bad landings and unbalanced landings. Given that the discrepancy in bad landing outcomes was primarily observed among the different disciplines rather than between sexes, the findings could imply that the variation in landing quality is not necessarily attributed to sex, but rather influenced by the unique characteristics of each discipline. Previous studies have also demonstrated a higher risk of injury and bad landing stability in snowboard compared to freeski, particularly in the context of Slopestyle (Linløkken, 2022, p. 56; Palmer et al., 2021, p. 970; Soligard et al., 2019, p. 1087; Soligard et al., 2015, p. 443). A potential explanation for the increased injury risk in snowboarders is the tendency for snowboarders to have a higher EFH values compared to skiers, although this difference is not statistically significant (table 9). Nonetheless, if the variation in landing quality between disciplines were due to higher EFH values, one would expect to observe a significant sex difference in landing quality, which is not the case in this project.

Another possible explanation for this discrepancy could be attributed to the equipment, as snowboarders have both feet attached to the board. Given that the supporting surface of the snowboard is fixed, it may be more challenging to halt the angular velocity and increase the likelihood of losing control during landing. In contrast, skiers can modify their support surface, enabling them to attain a more favorable landing position and making it potentially easier to halt the angular velocity and attain balance. However, there is no difference in landing outcomes between female ski and snowboard athletes regarding bad and unbalanced landings. Thus, there may be a psychological component contributing to the observed variation in landing outcomes across disciplines. According to Breivik et al. (2017, p. 269), men tend to be more risk and thrill seeking compared to women, potentially leading to male athletes executing more advanced maneuvers than their female counterparts. Nonetheless, as previously mentioned, we did not observe any difference in landing outcomes between sex. However, it is possible that the psychological aspect, combined with the limitations of snowboarding equipment, contributes to decreased landing quality. The execution of more complex tricks by male snowboarders may lead to larger imbalances, which in combination with equipment limitations, can result in more severe consequences compared to female snowboarders.

The incidents of falls by snowboarders observed in this study was 40,2 % (table 6), which is significantly higher than the 13,2 % reported by Linløkken (2022, p. 56) and the 21 % reported by Kurpiers et al. (2017, p. 2459). Furthermore, the incidents of falls among skiers in this study was 15,3 %, which is also significantly higher than the 5,8 % reported by Linløkken (2022, p. 56). The participants in this study had a higher skill level compared to those in the Kurpiers et al. (2017) study, who included active users of TP, which could be a contributing factor to the observed differences in fall incidents. Nevertheless, the discrepancy in fall percentage was even greater compared to the study of Linløkken (2022), which also involved elite athletes in the World Cup. A more likely explanation for the discrepancy could be due to differences in jump design between the studies. The study by Linløkken (2022, p. 71) had jump designs consisting of step-up and roll-over, while the study by Kurpiers et al. (2017, p. 2458) had a table-top design. The parabolic jump design in the study by Linløkken (2022) is in general considered safer as the landing aligns better with the athlete’s trajectory and occurs at a reduced velocity (Kulturdepartementet, n.d.). On the other hand, the step-down design used in this study is known for being challenging to adjust the correct speed to land in the sweet-spot, resulting in athletes experiencing high forces during landing (Kulturdepartementet, n.d.), as indicated by the high values of EFH in Table 9. This may explain the high percentage of falls observed in this study, which suggest that even experienced athletes may find the step-down jump unsafe, regardless of skill level.

6.3 EFH and rider behavior as predictors for landing stability

The logistic analysis revealed that neither EFH nor any of the included rider variables served as significant predictors for landing stability in both freeski and snowboarding (tables 10,11 & 12). Thus, all hypotheses must be dismissed. The outcome of the logistic regression analysis was unexpected and may be attributed to either chance or methodological limitations. The examination of landing stability predictors in freeski included only 32 athletes, as obtaining EFH data was only possible for this sample due to limited visibility. Furthermore, only five of these athletes exhibited landings with good stability, which may be insufficient to determine significant predictors of landing stability. The outcome of the analysis might be different if physical data on all athletes were available. It is possible that unaccounted factors prior to the athlete’s airborne state could have influenced the outcome, making the dataset insufficient to determine the factors impacting landing stability. Nevertheless, this project has conducted a comprehensive examination of various factors that may affect landing stability, similar to the analysis conducted by Linløkken (2022), which identified several significant predictors of landing stability. The absence of significant findings in the logistic regression analysis could be attributed to the high mean EFH values, as indicated in Table 9. Consequently, a sub-analysis was conducted to identify the predictors of EFH, which could potentially shed light on why no factors could predict landing stability. However, before delving into the sub-analysis, it is essential to present and discuss the rider behavior findings in relation to previous research, as no determination of injury risk was discovered.

6.4 Rider behavior

Male athletes had significantly higher values of airtime, ω_{avg}, and axial motion compared to female athletes, while no difference was observed between equipment (table 7). This is in contrast to the study of Linløkken (2022, p. 61), which observed a significant difference in all three rider variabilities both between sex and between equipment. The higher values of these three rider behavior variables found in male athletes support the assumption that male athletes execute more complex maneuvers than female athletes. The observed difference may be present due to multiple factors. One possible explanation is that men have a higher muscle-to-mass ratio, allowing them to perform more muscular work on the take-off, as evidenced by the higher values of pop observed in male snowboarders (table 9), leading to increased airtime. Additionally, the ability of men to perform more muscular work on the take-off may allow them to create more angular momentum, resulting in higher values of ω_{avg}. Another possible contributing factor is the psychological difference between sex, where men are more thrill-seeking and may have a more competitive environment (Breivik et al., 2017, p. 268).

The prevalence of multiaxial maneuvers among male athletes, and to a significantly greater extent than female athletes, suggests that multiaxial maneuvers may be more complex compared to monoaxial maneuvers. This claim is based on the premise that male athletes tend to be more thrill-seeking, possess physical advantages, and are likely to participate in a more competitive environment compared to their female counterparts. Moreover, it is hypothesized that athletes perform more spectacular tricks with a higher level of difficulty in Big Air than in Slopestyle due to increased airtime and the performance of only one single jump. In this study, 75,1 % of snowboard maneuvers were executed multiaxially, while Linløkken (2022, p. 61) found that multiaxial maneuvers accounted for only 34,1 %. This significant difference in the percentage of snowboarders performing multiaxial maneuvers between the two disciplines supports the argument that multiaxial maneuvers are more complex to perform. However, the findings from Linløkken (2022, p. 76) suggest that in skiers, monoaxial maneuvers may be more challenging to execute with increased values of $\omega_{avg,}$ while multiaxial maneuvers may be more challenging with low values of ω_{avg}. Nevertheless, the increased difficulty of executing multiaxial maneuvers at low ω_{avg} in elite athletes may not hold practical relevance, considering that such maneuvers require a greater amount of angular momentum to complete the maneuver successfully. Based on the findings of Linløkken (2022, p. 76) and the high values of ω_{avg} in both male and female athletes in this thesis (table 7), it is conceivable that performing multiaxial maneuvers may be less challenging compared to monoaxial maneuvers. As a result, the greater difficulty typically associated with multiaxial maneuvers with a smaller ω_{avg} may not necessarily apply to the context of Big air. In this study, ω_{avg} was calculated in total based on the number of rotations divided by airtime and not in the various axes. It is possible that at the same ω_{avg}, a multiaxial maneuver where the angular velocity is distributed around different axes is easier to land compared to a monoaxial maneuver where the momentum is entirely around the vertical axis. Additionally, a multiaxial maneuver will occur around several axes which may provide a better landing overview for the athlete compared to a monoaxial maneuver.

According to Hubbard (2009, p. 182), if the airtime is around 2 seconds, there is a possibility of compromised control of the body composition. In this study, the average airtime of all groups exceeded 2 seconds. Furthermore, in this study, the skiers and snowboarders achieved higher airtimes of 2,22 and 2,20, respectively, compared to the airtimes of 2,02 and 1,94 observed at Seiser Alm (Linløkken, 2022, p. 61). Additionally, the ω_{avg} values in this study were 472 and 451, while Seiser Alm observed ω_{avg} values of 447 and 349 for skiers and snowboarders, respectively. Although the specific number of rotations was not provided in either study, it is reasonable to assume that the number of rotations is a product of both airtime and ω_{avg}. Consequently, based on the athletes in this study having both increased airtime and ω_{avg} in comparison to those in Seiser Alm, it can be inferred that the athletes in this study performed more complex maneuvers with a higher number of rotations. The higher values of airtime observed in this study can likely be attributed to the step-down design utilized. However, elite athletes possess exceptional body control, which may enable them to maintain control during airtimes exceeding 2 seconds. Nevertheless, differences in rider behavior variables that could potentially impact the complexity of a maneuver were found between sex, which contrasts with the landing quality differences that were mainly observed between equipment. This suggests that rider behavior variables may not be a determining factor for landing quality. This is reinforced by the observation that male skiers had significantly higher values of airtime and axial motions, as well as a tendency towards higher ω_{avg} than male snowboarders, yet male snowboarders had a greater incidence of both fall, bad landings, and unbalanced landings.

The only difference in rider orientation was observed between male and female skiers, with male skiers exhibiting a greater frequency of switch take-offs (table 8). This disparity could indicate that performing switch take-offs poses a greater challenge for skiers since male athletes tend to execute more advanced maneuvers in comparison to their female counterparts. However, in the case of male skiers, the distribution of rider orientation (switch and normal) during take-off and landing is quite similar, indicating a balanced representation. Conversely, there appears to be a tendency towards more switch landings among female skiers. This observation may indicate that elite athletes can adapt to the biomechanical differences associated with rider orientation without difficulty (Löfquist & Björklund, 2020, p. 1569). Snowboarders exhibited a higher frequency of normal orientation during both take-off and landing, with no significant sex differences. This observation potentially suggests that snowboarders experience greater challenges regarding switch landings, implying a potential lack of control in that orientation, regardless of there being no biomechanical difference between the two rider orientations. Additionally, snowboarders exhibited a greater frequency of backside rotation, with no significant sex difference. Kurpiers et al. (2017, p. 2459) observed a higher incidence of falls among athletes performing backside rotations, suggesting that backside rotations enhance the level of difficulty of the maneuver in comparison to frontside rotations. This finding may provide an explanation of the prevalence of backside rotations observed in the current study. It is plausible that a backside rotation adds complexity to the maneuver, which could potentially result in higher scores for the athlete. In contrast, the lower occurrence of frontside rotations among athletes could be attributed to the increased complexity associated with executing such maneuvers. The complexity of frontside rotation stems from the hypothesis put forth in our study, suggesting that the diminished degree of freedom during landing occurs when athletes rotate towards the heel edge of the board while preferring to land on the toe edge. However, it is challenging to determine which rider behavior variations are the most complex as the athlete’s performance is not included in the analysis. Therefore, we can only make assumptions about what is most likely to increase the level of difficulty. Neither rider orientation upon landing nor rotational direction were primary predictors for landing stability in this study. Further research is required to determine which specific combinations of rider orientation and directional rotation that pose the greatest level of complexity.

6.5 Equivalent fall height

EFH was not a primary predictor of landing stability. Contrary to prior research that suggests EFH as the most critical factor impacting jump safety, an increase in EFH did not result in a higher likelihood of bad landing stability (Hubbard, 2009, p. 182;

Linløkken, 2022, pp. 66-67; McNeil et al., 2012, p. 6; Moore et al., 2021, p. 6; Swedberg & Hubbard, 2012, p. 122). The findings in the study of Linløkken (2022, pp. 66-67), indicate a higher probability for bad landing stability in all groups with an increase in EFH. One possible explanation for the lack of such findings in this study could be attributed to the considerably higher EFH values (table 9). The mean EFH values in this study were 1,69 m and 1,48 m for male skiers and male snowboarders, respectively. In comparison, the reported EFH values for male skiers and male snowboarders in Seiser Alm were 0,49 m and 0,51 m, respectively (Hoholm, 2022, p. 72). This corresponds to EFH values approximately three times higher than those found in Slopestyle (Hoholm, 2022, p. 72; Linløkken, 2022, p. 58). The values of this thesis approach the maximum EFH value of 1,5 m, as suggested by Minetti et al. (1998, p. 1789), which represents the limit that an elite jumper can absorb in the legs. Therefore, it is plausible that once EFH reaches a certain level, the impact of different rider behavior variables on landing stability diminishes. One plausible explanation is that the impact experienced upon landing surpasses the athlete's ability to absorb in their legs, regardless of their ability to maintain balance while airborne and upon landing, and land with the equipment parallel to the slope. Consequently, athletes who land with an undetected slight unbalance may be at risk of falling. Moreover, it is conceivable that only the strongest athletes are capable of withstanding the significant forces upon landing. As a result, athletes performing tricks that are theoretically considered to have a lower degree of difficulty may experience a similar frequency of bad landing quality as those executing more challenging tricks. This aspect could contribute to the lack of significant findings in terms of determining injury risk factors. The dataset included EFH values ranging from 0,85 m to 3,67 m, with most values exceeding the recommended limit of 1 m by Hubbard and Swedberg (2012, p. 3).

The sub-analysis was utilized to determine if $V_{Parallel}$, pop, drop height, and landing angle could predict EFH. The results showed that the models were significant in both freeski and snowboarding (tables 13-16). Both drop height and landing angle were found to be significant predictors of EFH, with an increase in these variables increasing EFH (tables 14 & 16). These findings are consistent with previous research, which emphasizes the importance of the landing angle matching the athlete's flight path to ensure safe landings (Hubbard, 2009, p. 178; Hubbard & Swedberg, 2012, p. 3; McNeil et al., 2012, p. 6; Swedberg & Hubbard, 2012, p. 122). Furthermore, in snowboarding, pop was found to be a significant predictor of EFH, where an increase in pop led to a decrease in EFH (table 16). The observed relationship between pop and EFH in snowboarding may be attributed to the limited ability of snowboarders to adjust their posture, as suggested by Wolfsperger et al. (2021, p. 1085). Thus, snowboarders may need to generate a larger “pop” to ensure a successful landing in the sweet spot.

The mean landing angle for male skiers and male snowboarders was 17,67° and 18,54°, respectively (table 9). This is higher compared to the reported landing angles for male skiers and male snowboarders in Slopestyle in Seiser Alm, which were 12,96° and 13,21°, respectively (Hoholm, 2022, p. 72). The mean drop height for male skiers in this study was 13,06 m, while for male snowboarders it was 10,94 m. In comparison, the drop height for skiers and snowboarders in Seiser Alm was 6,50 m and 6,17 m, respectively (M. Gilgien, personal communication, May 16, 2023). Unfortunately, it was not possible to calculate the drop height within subgroups in Seiser Alm. However, our findings indicate significantly higher values for female snowboarders, with a mean drop height of 9,44 m compared to the mean drop height observed in snowboarders in Seiser Alm. It’s important to note that these results represent the mean value of the three jumps in Seiser Alm combined. The drop height differs among the three jump designs, but all are considerably lower than what was observed in this study.

Furthermore, our study observed a considerably longer mean horizontal jump distance (table 9) compared to the Slopestyle event in Seiser Alm (Hoholm, 2022, p. 72). This finding is consistent with the research of Swedberg and Hubbard (2012, p. 129), who demonstrated a linear relationship between EFH and horizontal jump distance on a tabletop jump. Two EFH values exceeding 3 m stood out as they pose a high impact risk that might result in serious injuries (Moore et al., 2021, p. 6; Petrone et al., 2017, p. 290). These two values can be attributed to longer horizontal jump distance and align with previous research indicating that overjumping is the most critical design parameter (Böhm & Senner, 2008, p. 170; McNeil et al., 2012, p. 16; Swedberg & Hubbard, 2012, p. 129). Therefore, the longer mean horizontal jump distance in our study may account for the higher EFH values. It is worth noting that jump 2 in the study conducted by Linløkken (2022, p. 60) had comparable horizontal jump distance values to those observed in this study. However, the EFH values on jump 2 were lower compared to this study despite similar horizontal jump distance. This discrepancy in EFH values could be attributed to the fact that jump 2 in the study of Linløkken (2022) utilized a roll-over jump design (Hoholm, 2022, p. 64). The roll-over jump design likely resulted in a minimum drop height, lower landing speed, and reduced landing angle compared to the step-down design utilized in this study (Kulturdepartementet, n.d.).

There was no significant difference found in $V_{Parallel}$ between the studies, but this factor was not identified as a significant predictor in the models (tables 14 & 16). The disparity in landing angle and drop height between this study and the study in Seiser Alm accounts for the large EFH values observed in this project. The athletes had a mean horizontal landing position at a landing surface angle of 38 ° (figure 11), which is typically considered adequate to reduce landing impact. However, the mean landing angle, drop height and EFH were dangerously high, indicating that the step-down jump may pose a significant injury risk even if the basic recommendations for jump designs are followed. One could argue that longer airtimes allow for more challenging tricks to be performed, resulting in a higher degree of difficulty. Combined with a high EFH, this may lead to the higher observed proportion of falls, bad landings, and unbalanced landings compared to Seiser Alm. Previous research has highlighted EFH as the most important factor in terms of injury risk. Therefore, based on our empirical data, it is reasonable to assume that Minetti et al. (1998, p. 1789) recommendation of 1,5 m EFH should not be exceeded. Moreover, it is worth considering that this recommendation may be excessively high, given the prevalence of falls, bad landings, and unbalanced landings observed in our study compared to previous studies with a substantially lower EFH value. This potentially indicates that the recommendation proposed by Hubbard (2009, p. 179) of a 1m EFH value is more accurate and that the EFH values should not exceed this threshold to ensure the safety of the athletes.

7. Limitations

This thesis is a component of a broader ongoing project that covers several years and includes a dataset from a Big air World Cup event in the 2016/2017 season. As a relatively new sport that is continuously evolving, the tricks and jumps become increasingly impressive each year, with the athletes always striving to push the boundaries of what is possible. Present-day athlete’s probable executes tricks with a greater complexity than those included in this project’s dataset, thereby calling into question the reliability of the analysis results in providing insight into current competitions. Future research should investigate the impact of rider behavior on landing stability in contemporary athletes.

The manual annotation of the athlete’s COM is also susceptible to errors. In some photos, distinguishing the athlete from the background was impossible, and in some cases, the athlete was not visible before take-off. Consequently, manual annotation of the COM was excluded in these frames. This process is time-consuming and can easily result in errors. Therefore, one can question the validity of manual annotation to locate the COM. Nonetheless, the flight path was computed through the average position of the COM, which compensated for a small margin of errors with a smooth curve. Additionally, the manual annotation was conducted by two observers, which may have different interpretations of where to place the COM. A clear definition was established to place the COM at the hip level. However, this specification may introduce a margin of error and potentially reduce interrater reliability. The limited availability of physical data on skiers was due to the difficulties in annotation of the COM of athletes throughout the run. Only one female skier had physical data available, which prevented including female skiers in the analysis. Furthermore, physical data was calculated for only 32 male skiers, potentially limiting the validity of the results. In future studies, potential injury risk factors should be investigated using a more comprehensive dataset on skiers.

The challenge of distinguishing athletes from the background during evening sessions may have resulted in imprecisions in the subjective evaluation of rider behavior, particularly regarding the timing of take-off and landing. The low quality of some of the videos and athletes landing behind the floodlights made it challenging to distinguish the athletes from the background, which could have resulted in errors in the analysis. In certain videos, landing quality could not be assessed due to the athlete’s disappearance from the camera angle. Additionally, a banner placed at the edge of the jump in the finals made it challenging to determine the exact take-off moment. Finally, some male athletes executed a “butter” maneuver before take-off, which created a snow cloud and obstructed the take-off moment. The assessment of the type of maneuver and the axis of rotation may be prone to error as the position of the athlete’s head was difficult to observe in some situations. This thesis defines a cork as a maneuver where the athlete’s head is horizontal with the equipment, but in reality, a cork can involve spinning only a small part out of the original vertical axis. However, this definition is utilized to simplify the subjective analysis and has been employed in previous projects. The subjective analysis was conducted separately by two observers, and in cases where discrepancies were found between their assessments, the videos were reviewed and discussed to reach a consensus agreement, enhancing the interrater reliability.

Only imbalances resulting from mechanisms occurring after take-off was considered in the identification of potential injury risk factors. However, future research should also investigate the mechanisms that occur before and during take-off, as athletes may already be out of balance in the airborne phase. Unfortunately, due to limited visibility of the take-off phase and challenges in accurately defining imbalances during the airborne phase, it was not feasible to investigate these mechanisms in this thesis. Future research should consider the effect of grabbing the equipment and its impact on performance and landing stability. Kurpiers et al. (2017, p. 2459) found that grabbing the board in snowboarding reduced the probability of falling. However, the low-quality videos prevented its inclusion in this thesis.

Another limitation of this study is that landing stability is used as a surrogate measure, which limits the ability to compare the results with other studies that have examined actual injury rates. However, it should be noted that the focus of this project was not to examine the true injury rate, but rather to investigate the impact of EFH and rider behavior on landing stability.

8. Practical implications

To the best of our knowledge, this is the first study to explore the impact of EFH and rider behavior on landing stability among elite athletes participating in a Big air event. This thesis contributes to the literature by providing empirical evidence on the relationship between landing impact and potential injury risk, using landing stability as a surrogate measure. Hence, this thesis can provide new insight and establish a basis for future research and theoretical developments. This knowledge is valuable for both athletes, coaches, judges, and the academic community.

9. Conclusion

In conclusion, it was not possible to identify specific factors that could determine the potential injury risk in snowboarding and freeski. However, snowboard athletes had a higher proportion of falls, bad landings, and unbalanced landings, which may be due to their limited range of motion compared to skiers. The observed high EFH values may be a contributing factor for the high incidence of falls, bad landings, and unbalanced landings. The high mean EFH values may diminish the impact of various factors on landing quality. Additionally, drop height and landing angle were found to be significant predictors of EFH. The results indicate that large step-down jumps lead to high values of EFH, highlighting the importance of designing jumps where the landing matches the flight path of the athlete. The results indicate the importance to avoid exceeding the USTPC criterion of a maximum acceptable EFH of 1,5 m. Furthermore, it raises concerns that the current EFH criterion might be too high to ensure the safety of the athletes. Future research should investigate the impact of rider behavior and EFH on landing stability across a wider range of EFH values. By expanding the range of EFH values, researchers can gain a more comprehensive understanding of how these variables interact, and their influence on landing stability and rider behavior.

References

Audet, O., Hagel, B. E., Hamel, D., Tremblay, B., Macpherson, A. K., & Goulet, C. (2021). The association between removing and reintroducing man-made jumps in terrain parks and severe alpine skiing and snowboarding injuries. *J Sci Med Sport*, *24*(3), 212-217. https://doi.org/10.1016/j.jsams.2020.08.002

Bakken, A., Bere, T., Bahr, R., Kristianslund, E., & Nordsletten, L. (2011). Mechanisms of injuries in World Cup Snowboard Cross: a systematic video analysis of 19 cases. *British Journal of Sports Medicine*, *45*(16), 1315-1322.

Breivik, G., Sand, T. S., & Sookermany, A. M. (2017). Sensation seeking and risk-taking in the Norwegian population. *Personality and Individual Differences*, *119*, 266-272. https://doi.org/10.1016/j.paid.2017.07.039

Brooks, M. A., Evans, M. D., & Rivara, F. P. (2010). Evaluation of skiing and snowboarding injuries sustained in terrain parks versus traditional slopes. *Injury Prevention (1353-8047)*, *16*(2), 119-122. https://doi.org/10.1136/ip.2009.022608

Böhm, H., & Senner, V. (2008). Safety in big jumps: relationship between landing shape and impact energy determined by computer simulation. *Journal of ASTM International*, *5*(8), 1-11. https://doi.org/10.1520/JAI101381

Carús, L., & Escorihuela, M. (2016a). Epidemiology of Feature-Specific Injuries Sustained by Skiers in a Snow Park. *Wilderness Environ Med*, *27*(3), 415-420. https://doi.org/10.1016/j.wem.2016.05.001

Carús, L., & Escorihuela, M. (2016b). Feature-specific ski injuries in snow parks. *Accident Analysis & Prevention*, *95*, 86-90. https://doi.org/10.1016/j.aap.2016.06.023

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *J Biomech*, *29*(9), 1223-1230. https://doi.org/10.1016/0021-9290(95)00178-6

Fédération Internationale de Ski. (2018). *The International Freestyle Skiing Competition Rules (ICR)*. Book V Joint Regulations For Freestyle Skiing. Retrived 17. February 2022, from https://assets.fis-ski.com/image/upload/v1542730293/fis-prod/FS_FIS_Freestyle_ICR_2018_Fall_marked-up.pdf

Fédération Internationale de Ski. (2019). *JUDGES HANDBOOK SNOWBOARD & FREESKI* Retrived 17. February 2022, from https://assets.fis-ski.com/image/upload/v1610953451/fis-prod/assets/FIS_SB_FK_JudgesHandbook_20_21.pdf

Fédération Internationale de Ski. (2022). *THE INTERNATIONAL SNOWBOARD / FREESTYLE / FREESKI COMPETITION RULES (ICR)*. INTERNATIONAL SKI AND SNOWBOARD FEDERATION. Retrived 17. February 2022, from https://assets.fis-ski.com/image/upload/v1669644592/fis-prod/assets/SBFSFK_NEW_ICR_fall_2022_clean.pdf#page=84&zoom=100,72,594

Flørenes, T. W., Heir, S., Nordsletten, L., & Bahr, R. (2010). Injuries among World Cup freestyle skiers. *Br J Sports Med*, *44*(11), 803-808. https://doi.org/10.1136/bjsm.2009.071159

Goulet, C., Hagel, B., Hamel, D., & Légaré, G. (2007). Risk factors associated with serious ski patrol-reported injuries sustained by skiers and snowboarders in snow-parks and on other slopes. *Can J Public Health*, *98*(5), 402-406. https://doi.org/10.1007/bf03405428

Hauk, M., Hirt, C., & Ackermann, C. (2017). Experiences with the QDaedalus system for astrogeodetic determination of deflections of the vertical. *Survey review*, *49*(355), 294-301. https://doi.org/10.1080/00396265.2016.1171960

Hoholm, S. L. (2022). *"Pop" and its relation to performance factors and equivalent fall height in World Cup slopestyle for skiers and snowboarders (Master's thesis)* Norwegian School of Sport Sciences].

Hubbard, M. (2009). Safer Ski jump landing surface design limits normal impact velocity. *Journal of ASTM International 6(1)*, 175-183. https://doi.org/10.1520/jai101630

Hubbard, M., McNeil, J. A., Petrone, N., & Cognolato, M. (2015). Impact performance of standard tabletop and constant equivalent fall height snow park jumps. *Skiing trauma and safety*, *20*, 51-71. https://doi.org/10.1520/STP158220140027

Hubbard, M., & Swedberg, A. (2012). Design of Terrain Park jump landing surfaces for constant equivalent fall height is robust to "Uncontrollable" factors. In *Skiing trauma and safety: 19th volume* (Vol. 19, pp. 75-94). ASTM International. https://doi.org/10.1520/STP104515

Idzikowski, J. R., Janes, P. C., & Abbott, P. J. (2000). Upper extremity snowboarding injuries. Ten-year results from the Colorado snowboard injury survey. *Am J Sports Med*, *28*(6), 825-832. https://doi.org/10.1177/03635465000280061001

International Olympic Committee. (2021a). *Freestyle skiing*. Olympic Channel Services. Retrieved 30. May 2022, from https://olympics.com/en/sports/freestyle-skiing/

International Olympic Committee. (2021b). *Snowboard*. Olympic Channel Services. Retrieved 30. May 2022, from https://olympics.com/en/sports/snowboard/#discipline-history-of

Johnsson, C., Laureshyn, A., & De Ceunynck, T. (2018). In search of surrogate safety indicators for vulnerable road users: a review of surrogate safety indicators. *Transport Reviews*, *38*(6), 765-785. https://doi.org/10.1080/01441647.2018.1442888

Kim, S., Endres, N. K., Johnson, R. J., Ettlinger, C. F., & Shealy, J. E. (2012). Snowboarding Injuries: Trends Over Time and Comparisons With Alpine Skiing Injuries. *American Journal of Sports Medicine*, *40*(4), 770-776. https://doi.org/10.1177/0363546511433279

Kröll, J., Spörri, J., Steenstrup, S. E., Schwameder, H., Müller, E., & Bahr, R. (2017). How can we prove that a preventive measure in elite sport is effective when the prevalence of the injury (eg, ACL tear in alpine ski racing) is low? A case for surrogate outcomes. *British Journal of Sports Medicine*, *51*(23), 1644-1645. https://doi.org/10.1136/bjsports-2016-097020

Kulturdepartementet. (n.d.). *Designe en Snowpark*. Retrived 13.01.2023 from https://snowpark.no/designe-en-snowpark/

Kurpiers, N., McAlpine, P., & Kersting, U. G. (2017). Predictors of falls in recreational snowboard jumping: An observational study. *Injury*, *48*(11), 2457-2460. https://doi.org/10.1016/j.injury.2017.08.052

Levy, D., Hubbard, M., McNeil, J. A., & Swedberg, A. (2015). A design rationale for safer terrain park jumps that limit equivalent fall height. *Sports Engineering*, *18*(4), 227-239. https://doi.org/10.1007/s12283-015-0182-6

Lin, T.-Y., Dollár, P., Girshick, R., He, K., Hariharan, B., & Belongie, S. (2017). Feature pyramid networks for object detection. *Proceedings of the IEEE conference on computer vision and pattern recognition*, 2117-2125.

https://openaccess.thecvf.com/content_cvpr_2017/papers/Lin_Feature_Pyramid_Networks_CVPR_2017_paper.pdf

Linløkken, M.-S. (2022). *A biomechanical analysis of how rider behavior and equivalent fall height affect landing stability in World Cup Slopestyle for freeski and snowboard (Master's thesis)*. Norwegian School of Sport Sciences].

Löfquist, I., & Björklund, G. (2020). What Magnitude of Force is a Slopestyle Skier Exposed to When Landing a Big Air Jump? *International journal of exercise science*, *13*(1), 1563-1573. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7745909/

Major, D. H., Steenstrup, S. E., Bere, T., Bahr, R., & Nordsletten, L. (2014). Injury rate and injury pattern among elite World Cup snowboarders: a 6-year cohort study. *Br J Sports Med*, *48*(1), 18-22. https://doi.org/10.1136/bjsports-2013-092573

Martínková, I., & Parry, J. (2020). Olympic winter games,'cold sports', and inclusive values. *The International Journal of the History of Sport*, *37*(13), 1236-1251. https://doi.org/10.1080/09523367.2020.1860942

McNeil, J. A. (2012a). The Inverting Effect of Curvature in Winter Terrain Park Jump Takeoffs. *Skiing Trauma and Safety: 19th Volume (RJ Johnson, 537 JE Shealy, RM Greenwald, and IS Scher, eds.)*, 136-150.

McNeil, J. A. (2012b). Modeling the" pop" in winter terrain park jumps. *ASTM International*, 1-14. https://doi.org/10.1520/STP104240

McNeil, J. A., Hubbard, M., & Swedberg, A. D. (2012). Designing tomorrow's snow park jump. *Sports Engineering*, *15*(1), 1-20. https://doi.org/10.1007/s12283-012-0083-x

McNeil, J. A., & McNeil, J. B. (2009). Dynamical analysis of winter terrain park jumps. *Sports Engineering*, *11*(3), 159-164. https://doi.org/10.1007/s12283-009-0013-8

Minetti, A. E., Ardigò, L. P., Susta, D., & Cotelli, F. (1998). Using leg muscles as shock absorbers: theoretical predictions and experimental results of drop landing performance. *Ergonomics*, *41*(12), 1771-1791. https://doi.org/10.1080/001401398185965

Moffat, C., McIntosh, S., Bringhurst, J., Danenhauer, K., Gilmore, N., & Hopkins, C. L. (2009). Terrain park injuries. *The western journal of emergency medicine*, *10*(4), 257-262. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2791729/

Moore, J., Cloud, B., Hubbard, M., & Brown, C. A. (2021). Safety-Conscious Design of Terrain Park Jumps: Ethical Issues and Online Software. *EngrXiv Preprints*, 1-16. https://doi.org/10.31224/osf.io/sq7u9

Moore, J. K., & Hubbard, M. (2018). skijumpdesign: A ski jump design tool for specified equivalent fall height. *Journal of Open Source Software*, *3*(28), 818. https://doi.org/10.21105/joss.00818

Palmer, D., Engebretsen, L., Carrard, J., Grek, N., Königstein, K., Maurer, D. J., Roos, T., Stollenwerk, L., Tercier, S., Weinguni, R., & Soligard, T. (2021). Sports injuries and illnesses at the Lausanne 2020 Youth Olympic Winter Games: a prospective study of 1783 athletes from 79 countries. *Br J Sports Med*, *55*(17), 968-974. https://doi.org/10.1136/bjsports-2020-103514

Peng-da Han, D. G., Liu, J., Lou, J., Tian, S.-j., Lian, H.-x., Niu, S.-m., Zhang, L.-x., Wang, Y., & Zhang, J.-j. (2022). Medical services for sports injuries and illnesses in the Beijing 2022 Olympic Winter Games. *World Journal of Emergency Medicine*, *13*(6), 459-466. https://doi.org/10.5847/wjem.j.1920-8642.2022.106

Petrone, N., Cognolato, M., McNeil, J. A., & Hubbard, M. (2017). Designing, building, measuring, and testing a constant equivalent fall height terrain park jump. *Sports Engineering*, *20*(4), 283-292. https://doi.org/10.1007/s12283-017-0253-y

Randjelovic, S., Heir, S., Nordsletten, L., Bere, T., & Bahr, R. (2014). Injury situations in Freestyle Ski Cross (SX): a video analysis of 33 cases. *British Journal of Sports Medicine*, *48*(1), 29-35. https://doi.org/10.1136/bjsports-2012-091999

Reid, R. C. (2010). *A kinematic and kinetic study of alpine skiing technique in slalom (PhD)* Norwegian School of Sport Sciences].

Ruedl, G., Schobersberger, W., Pocecco, E., Blank, C., Engebretsen, L., Soligard, T., Steffen, K., Kopp, M., & Burtscher, M. (2012). Sport injuries and illnesses during the first Winter Youth Olympic Games 2012 in Innsbruck, Austria. *Br J Sports Med*, *46*(15), 1030-1037. https://doi.org/10.1136/bjsports-2012-091534

Rugg, C. D., Malzacher, T., Ausserer, J., Rederlechner, A., Paal, P., & Ströhle, M. (2021). Gender differences in snowboarding accidents in Austria: a 2005–2018 registry analysis. *BMJ open*, *11*(10), 1-9. https://doi.org/10.1136/bmjopen-2021-053413

Russell, K., Meeuwisse, W., Nettel-Aguirre, A., Emery, C. A., Wishart, J., Romanow, N. T. R., Rowe, B. H., Goulet, C., & Hagel, B. E. (2013). Characteristics of Injuries Sustained by Snowboarders in a Terrain Park. *Clinical Journal of Sport Medicine*, *23*(3), 172-177. https://doi.org/10.1097/JSM.0b013e31827bd918

Russell, K., Meeuwisse, W. H., Nettel-Aguirre, A., Emery, C. A., Wishart, J., Romanow, N. T., Rowe, B. H., Goulet, C., & Hagel, B. E. (2014). Feature-specific terrain park-injury rates and risk factors in snowboarders: a case-control study. *Br J Sports Med*, *48*(1), 23-28. https://doi.org/10.1136/bjsports-2012-091912

Rønning, R., Rønning, I., Gerner, T., & Engebretsen, L. (2001). The efficacy of wrist protectors in preventing snowboarding injuries. *Am J Sports Med*, *29*(5), 581-585. https://doi.org/10.1177/03635465010290051001

Schmidt, R. A., Lee, T. D., Winstein, C. J., Wulf, G., & Zelaznik, H. N. (2019). *Motor control and learning : a behavioral emphasis* (Sixth edition. ed.). Human Kinetics.

Schorr, M., Dichtel, L. E., Gerweck, A. V., Valera, R. D., Torriani, M., Miller, K. K., & Bredella, M. A. (2018). Sex differences in body composition and association with cardiometabolic risk. *Biology of sex differences*, *9*, 1-10. https://doi.org/10.1186/s13293-018-0189-3

Shealy, J., Scher, I., Stepan, L., & Harley, E. (2011). Jumper kinematics on terrain park jumps: relationship between takeoff speed and distance traveled. In *Skiing Trauma and Safety, 18th Volume* (pp. 173-186). ASTM International.

Soligard, T., Palmer, D., Steffen, K., Lopes, A. D., Grant, M.-E., Kim, D., Lee, S. Y., Salmina, N., Toresdahl, B. G., Chang, J. Y., Budgett, R., & Engebretsen, L. (2019). Sports injury and illness incidence in the PyeongChang 2018 Olympic Winter Games: a prospective study of 2914 athletes from 92 countries. *British Journal of Sports Medicine*, *53*(17), 1085-1092. https://doi.org/10.1136/bjsports-2018-100236

Soligard, T., Steffen, K., Palmer-Green, D., Aubry, M., Grant, M.-E., Meeuwisse, W., Mountjoy, M., Budgett, R., & Engebretsen, L. (2015). Sports injuries and illnesses in the Sochi 2014 Olympic Winter Games. *British Journal of Sports Medicine*, *49*(7), 441-447. https://doi.org/10.1136/bjsports-2014-094538

Steenstrup, S. E., Bere, T., & Bahr, R. (2014). Head injuries among FIS World Cup alpine and freestyle skiers and snowboarders: a 7-year cohort study. *Br J Sports Med*, *48*(1), 41-45. https://doi.org/10.1136/bjsports-2013-093145

Steffen, K., Moseid, C. H., Engebretsen, L., Søberg, P. K., Amundsen, O., Holm, K., Moger, T., & Soligard, T. (2017). Sports injuries and illnesses in the Lillehammer 2016 Youth Olympic Winter Games. *Br J Sports Med*, *51*(1), 29-35. https://doi.org/10.1136/bjsports-2016-096977

Swedberg, A., & Hubbard, M. (2012). Modeling terrain park jumps: linear tabletop geometry may not limit equivalent fall height. In *Skiing trauma and safety: 19th volume* (pp. 120-135). ASTM International. https://doi.org/10.1520/STP104335

Swedberg, A. D. (2010). *Safer Ski jumps: design of landing surfaces and clothoidal in-run transitions (Master's thesis)* NAVAL POSTGRADUATE SCHOOL MONTEREY CA]. https://apps.dtic.mil/sti/citations/ADA524748

Tarazi, F., Dvorak, M. F., & Wing, P. C. (1999). Spinal injuries in skiers and snowboarders. *Am J Sports Med*, *27*(2), 177-180. https://doi.org/10.1177/03635465990270021101

Torjussen, J., & Bahr, R. (2005). Injuries among competitive snowboarders at the national elite level. *Am J Sports Med*, *33*(3), 370-377. https://doi.org/10.1177/0363546504268043

Torjussen, J., & Bahr, R. (2006). Injuries among elite snowboarders (FIS Snowboard World Cup). *Br J Sports Med*, *40*(3), 230-234. https://doi.org/10.1136/bjsm.2005.021329

Van Mechelen, W., Hlobil, H., & Kemper, H. C. (1992). Incidence, severity, aetiology and prevention of sports injuries: a review of concepts. *Sports medicine*, *14*, 82-99. https://doi.org/10.2165/00007256-199214020-00002

Vernillo, G., Pisoni, C., & Thiébat, G. (2018). Physiological and physical profile of Snowboarding: a preliminary review. *Frontiers in physiology*, *9*, 1-7. https://doi.org/10.3389/fphys.2018.00770

Wolfsperger, F., Meyer, F., & Gilgien, M. (2021). Towards more valid simulations of slopestyle and big air jumps: Aerodynamics during in-run and flight phase. *J Sci Med Sport*, *24*(10), 1082-1087. https://doi.org/10.1016/j.jsams.2021.05.005

Wu, Y., Kirillov, A., Massa, F., Lo, W.-Y., & Girshick, R. (2019). Detectron2. Retrived 13. December 2022, from https://github.com/facebookresearch/detectron2

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Abbreviations

EFH	Equivalent fall height
USTPC	United State Terrain Park Council
FIS	The International Ski Federation
TP	Terrain Park
SB	Snowboard
COM	Centre Of Mass
CV	Computer Vision
ω_{avg}	Average angular velocity
$V_{Parallel}$	Velocity parallel
3D	Three-dimensional
CI	Confidence interval

Appendix 1 - Variables from observational assessment

The appendix presents an overview of the data set, including the variables obtained from the observational assessment of rider behavior. Additionally, it includes the physical data used in the analysis, which were obtained from the 3D trajectory. The physical variables included in the analysis are EFH, Drop height, Horizontal jump distance, Pop, $V_{Parallel}$, and Landing angle. There are other physical variables in the data set, but they were not utilized in the analysis and therefore are not presented. In the table, the variables are listed along with their corresponding cell name, whether they are continuous or categorical, the coding of the categorical variables in the data set (0 or 1), and an explanation of each variable. Furthermore, an explanation of the different maneuvers is provided at the end. SB=snowboard.

Cell	**Variable**	**Type**	**Coding**		**Explanation**
			0	**1**	
A	Cell identifier	Continuous			Each video has a number, reaching from 1 to 287. This is done to keep the data set organized.
B	Video number	Continuous			Each video has a registered video number from the cameras that were used to film.
C	Time	Continuous			Provide the starting time of the athlete’s run.
D	Disciplin	Categorical	Ski	SB	Offers details regarding the discipline to which the

Cell	Variable	Type	Coding		Explanation
			0	**1**	
	e				athlete belongs.
E	Bib number	Continuous			The start number of the athlete.
F	Sex	Categorical	Female	Male	Offers details regarding the sex of the athlete.
G	Group	Categorical	Ski_F = 1 Ski_M = 2 SB_F = 3 SB_M = 4		Provides information regarding the athlete's group affiliation: Ski Female (Ski_F), Ski Male (Ski_M), Snowboard Female (SB_F), or Snowboard Male (SB_M).
H	Heat	Categorical			Provide information regarding the competition phase of the athlete: First qualification (Q1), second qualification (Q2), or Finals.
I	Competition phase	Categorical	Q	F	Explaining if it was a qualification or final.

Cell	Variable	Type	Coding		Explanation
			0	1	
J	Run number	Continuous			Indicates whether it was the first (1), second (2), or third (3) run.
K & M	Rider orientation at take-off	Categorical	FW (Ski) Normal (SB)	SW (Ski) Switch (SB)	Provide information on whether the athlete had a forward/normal or switch position at take-off. In snowboarding, a normal rider orientation refers to when the athlete has their dominant foot in front, while switch refers to when they have their dominant foot in the back. K = SB M = Ski
L	The direction of rotation (SB)	Categorical	BS	FS	Explains whether the athlete performed a backside rotation (BS) or a frontside rotation (FS).
N	Axis	Categorical	Multi	Mono	Explains whether the athlete performed a multiaxial maneuver (Multi) or a monoaxial

Cell	Variable	Type	Coding		Explanation
			0	1	
					maneuver (Mono).
O	Rotation	Continuous			Provide information on the number of degrees the athletes are rotating.
P	Airtime	Continuous			Duration of the athlete's airborne time from the take-off lip to the landing.
Q	Angular velocity	Continuous			Rotation / Airtime
R & S	Rider orientation upon landing	Categorical	FW (Ski) Normal (SB)	SW (Ski) Switch (SB)	Provide information on whether the athlete had a forward/normal or switch position upon landing. R = SB S = Ski

Cell	Variable	Type	Coding		Explanation
			0	**1**	
T	Landing events	Categorical	Good= 1 Slight Unbalance= 2 Touch= 3 Fall= 4		Observational assessment of the landing balance of the athletes upon landing. Good: Clean landings without any noticeable imbalances. Slight unbalance: Some imbalances are observed, but the athletes manage to regain their balance without difficulties. Touch: Imbalances that result in touching the slope with a body part. Fall: The athletes are unable to regain their balance, leading to a fall.
U	Fall	Categorical	Good	Fall	Good: If the balance were good, slight unbalanced, or touch. Fall: If the athlete fell. Perspective 1 on landing quality.
V	Landing stability	Categorical	Good	Bad	Good: If the balance were good or slight unbalanced. Bad: If the balance were touch or fall. Perspective 2 on landing quality.

Cell	**Variable**	**Type**	**Coding**		**Explanation**
			0	**1**	
W	Landing balance	Categorical	Balanced	Unbalanced	Balanced: If the balance were good. Unbalanced: If the balance were slight unbalanced, touch or fall. Perspective 3 on landing quality.
X	Score	Continuous			The numerical rating of the athlete’s performance. Obtained from the FIS results.
Y	Weight	Continuous			The weight of the athletes
Z	Height	Continuous			The height of the athletes
AA	BMI	Continuous			Weight / height^2
AB	EFH	Continuous			Equivalent fall height, which explains the impact upon landing.

Cell	**Variable**	**Type**	**Coding**		**Explanation**
			0	**1**	
AE	Drop Height	Continuous			Provide information about the difference in height between the highest point reached while the athlete is airborne and the landing point.
AG	Horizontal jump distance	Continuous			Provide information on the horizontal jump distance of the athlete, measured from the take-off lip to the landing point.
AO	Take-off velocity parallel to the surface	Continuous			The velocity at which the athlete moves parallel to the take-off lip upon take-off.
AP	Pop	Continuous			Change in the velocity vector of the athlete resulting from the muscular work exerted at the take-off lip.

Cell	Variable	Type	Coding		Explanation
			0	**1**	
AR	Landing angle	Continuous			The angle difference between the athlete’s flight trajectory and the landing slope.
	Trick				This parameter was not included in the final data set: however, it was utilized to analyze the direction of rotations, the number of flips, and the axis of the maneuver. The maneuver was classified as single, double, or triple. <u>Ski & SB</u> Flip: Rotation around the frontal or sagittal axis. Frontflip: Clockwise rotation around the frontal axis. Backflip: Counter-clockwise rotation around the frontal axis. Sideflip: Rotation around the sagittal axis. Cork: An off-axis rotation that combines spins and counter-clockwise flips. The athlete never reaches a completely inverted

Cell	Variable	Type	Coding		Explanation
			0	1	
					position. The maneuver can be classified as single, double, or triple based on the number of partial inversions performed by the athlete. Underflip: An off-axis maneuver where the athlete performs a 90 degrees rotation on the take-off lip, followed by a counter-clockwise flip. The athlete's head flips beneath the equipment, resulting in a fully inverted position. <u>Freeski</u> Bio: An off-axis rotation that combines spins and clockwise flips. The athlete never reaches a completely inverted position. Misty: An off-axis maneuver that combines spin and clockwise flips. The athlete can reach a completely inverted position compared to a Bio. Rodeo: An off-axis maneuver that combines spin and counter-

Cell	Variable	Type	Coding		Explanation
			0	**1**	
					clockwise flips. The athlete can reach a completely inverted position compared to a Cork. <u>SB</u> Frontside rodeo: An off-axis maneuver that combines a counter-clockwise flip with 180 degrees frontside rotation. Backside rodeo: An off-axis maneuver that combines a clockwise flip with 180 degrees backside rotation.

Appendix 2 – Predictors of equivalent fall height

The variable predictor of EFH in male skiers did not incorporate residuals that followed a normal distribution, which is a fundamental requirement for linear regression. This deviation was attributed to the presence of two unusually high values of EFH. Consequently, the identical analyses presented in Tables 13 & 14 were carried out after excluding these two EFH values. As a result, the residuals exhibited a normal distribution, and the outcomes of these analyses are documented in Tables 17 & 18.

In the first model, neither $V_{Parallel}$ nor pop demonstrated significant predictive ability for EFH, leading to an overall non-significant model (table 17). The model was only able to predict 6,3% ($r^2 = 0,063$) of the variation in EFH.

Table 17: Variables in the model were tested with linear regression to evaluate whether $V_{Parallel}$ and pop could predict EFH in male skiers, with the two high values of EFH excluded. The beta-values were used to indicate the change in the predicted EFH for each one-unit increase in the independent variables, along with their corresponding 95% confidence intervals (lower and upper 95%CI) and p-value.

Independent variables	**Beta coefficients (standardized)**	**Lower 95%CI**	**Upper 95%CI**	**p-value**
Constant	-0,604	-3,995	2,787	0,717
$V_{Parallel}$ (m/s)	0,265	-0,088	0,407	0,198
Pop (m/s)	0,070	-0,159	0,224	0,731

One-way ANOVA = p > 0,05

The final model exhibited significant predictive ability for EFH ($p<0,001$) and accounted for 82,7 % ($r^2 = 0,900$) of the observed variation in EFH (table 18). Drop height ($p<0,5$), and landing angle ($p<0,001$), were found to be significant predictors of EFH, such that an increase in these variables would increase EFH corresponding to the values of the beta-coefficients. $V_{Parallel}$ and pop were not found to be significant predictors of the EFH outcome.

Table 18: Variables in the model were tested with linear regression to evaluate whether $V_{Parallel}$, pop, drop height, and landing angle could predict EFH in male skiers, with the two high values of EFH excluded. The beta-values were used to indicate the change in the predicted EFH for each one-unit increase in the independent variables, along with their corresponding 95% confidence intervals (lower and upper 95%CI) and p-value.

Independent variables	**Beta-coefficients (standardized)**	**Lower 95%CI**	**Upper 95%CI**	**p-value**
Constant	-1,857	-3,401	-0,314	0,020*
$V_{Parallel}$ (m/s)	-0,063	-0,163	0,087	0,539
Pop (m/s)	-0,042	-0,107	0,068	0,647
Drop height (m)	0,382	0,054	0,217	0,002*
Landing angle (°)	0,674	0,088	0,167	<0,001**

*= Coefficient (beta-value) of independent factor significantly different from 0 (p<0,05)
**= Coefficient (beta-value) of independent factor significantly different from 0 (p<0,001)
One-way ANOVA = p<0,001