NORWEGIAN SCHOOL
OF SPORT SCIENCES

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"Pop" and its relation to performance factors and equivalent fall height in World Cup slopestyle for skiers and snowboarders

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Abstract

Purpose: The aim of this study was to measure and investigate the “pop” performed by elite athletes in slopestyle skiing and snowboarding. Pop refers to the action an athlete performs at the end of the kicker (at the point of take-off), where an extension or contraction movement as a result of muscular work is used to adjust the take-off angle.

Methods: 273 individual trials were measured on three roll-over / step-up jumps during a slopestyle World Cup competition where male and female skiers and snowboarders participated. The snow surface was measured using a Lidar scanner, and jump profiles were derived from the data. A tachymetry-based video system (QDaedalus) along with computer vision were used to track and reconstruct the centre of mass trajectories. The trajectories and jump profile were used to calculate the parameters pop, jump distance, vertical jump height, velocity, take-off and landing angle, and equivalent fall height.

Results: In the 273 trials across the three jumps, pop ranged from -2.32 m/s to +2.20 m/s, where female skiers pop-ed at a mean of -0.29 m/s (± 0.71), male skiers at +0.07 m/s (± 0.71), female snowboarders at -0.17 m/s (± 0.66) and male snowboarders at +0.37 m/s (± 0.66). Skiers, snowboarders, female and male athletes landed at the same distance and approached the point of take-off with similar velocities. Snowboarder pop-ed 0.36 m/s more than skiers and male athletes pop-ed more than females. Males had longer flight time and higher vertical jump height compared with females, both in skiers and snowboarders. Furthermore, maximizing the pop was associated with both increased average angular velocity during flight, and flight time. At best there was a moderate negative relation between the velocity and pop (-0.546 within snowboarders), and the velocity and pop could only explain small parts (6.6%) of the variation observed in EFH. Adding landing angle to the model increased the explanatory power to 82.3%.

Conclusion: This study extends the knowledge on pop with data from elite athletes. Pop seems to be used as a tool to enhance performance through an increase in both flight time and average angular velocity / number of rotations to increase difficulty/progression and amplitude at the same time. Additionally, it was indicated that pop was used to regulate the jump distance to land in the “sweet spot”, and hence, optimize the landing impact, but pop had limited effect on EFH for the given jumps.

Content

Preface

This master thesis defines the end of six year long journey as a student within the course of study relating to sports biology and physical performance at the Norwegian School of Sport Sciences. Through lectures and meaningful discussions, I have learned a lot from knowleagable and experienced people that I look up to. I have also made great memories and friends that I will cherish for the rest of my life.

Needless to say (but I still will), the work on this thesis have been challenging and time consuming. However, it has also been exciting and a great learning experience, where I have learnt a lot about the whole research process, the amount of work put behind it, and also how one can adapt to unforseen circumstances. It has been exciting to perform work that could contribute to a better understanding of the elite athlete and to be part of something greater, and it has whet the appetite for more if an opportunity should arise.

First, I want to thank my supervisors, Matthias Felix Gilgien and Helge Spieker. From general guidence to essential work put into the project, I am very grateful! Thank you Matthias for being so enthusiastic about the project and always putting aside time for a good discussion and/or questions. It is inspiring to see someone with so much passion for what they do. Thank you Helge for always being open to discussion, providing support when needed, and taking me seriously even when I come up with “stupid” questions.

I also want to give a big thanks to my sister, Kine, and Knut for proofreading and supporting me in both great and tougher times, and to Petter and Frédéric for the work put into this project, the good cooperation, and genuinely nice conversations.

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Sindre Lindstad Hoholm

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1. Introduction

Freestyle skiing and snowboarding are sports that over the end of the 20th, and start of the 21st, century have gained a lot of popularity. The sports consist of different subdisciplines where athletes either compete by manoeuvring a course to be the fastest to the finish line or perform spectacular tricks to impress judges and the audience. The subdisciplines are getting a bigger platform to compete in and they are slowly, but surely, included more and more in the Olympics scene, with freestyle skiing slopestyle debuting in the 2022 Beijing Winter Olympics Games (Martínková & Parry, 2020). However, while the sports' popularity is increasing rapidly, injuries are a major issue. It has been observed that both the number and severity of injuries are among the worst in the world of winter sports (Engebretsen et al., 2010; Major et al., 2014; Soligard et al., 2015; Soligard et al., 2019). While the injuries vary, both in terms of the mechanisms and the body parts involved, there is a need to find ways to reduce injury risk in these sports, and especially in jumps, which seems to be one of the elements where most injuries are sustained (Tarazi et al., 1999; Torjussen & Bahr, 2006; Ehrnthaller et al., 2015; Levy et al., 2015). Ehrnthaller et al. (2015, p. 117) suggest that one of the main reasons for injuries sustained in the landing of jumps can be attributed to the impact the athlete needs to withstand in the landing being too high.

While there exist some standards for certain elements (rails, boxes, etc.), there exist no standard for the jumps that are used in parks and competition courses. Hence, it can be challenging for constructors, who have to fit the parts of a jump (inrun, kicker, deck and landing) together to ensure that an athlete's trajectory fit the design in jumps at all locations, and thus, could be improved with respect to injury prevention.

It has been observed that computer models can be used to simulate the jump kinematics and kinetics of athletes (Böhm & Senner, 2009; Hubbard, 2009; McNeil & McNeil, 2009; McNeil, 2012; McNeil et al., 2012; Levy et al., 2015). These allow for the computation of the landing impact, and velocity parallel to the snow surface ($V_{parallel}$) in jumps, based on the shape of the kicker and landing, inrun speed, air drag/lift, and knowledge of the skier's action at take-off ("pop") on the direction of the flight trajectory (McNeil, 2012). While such software is applied in the park builder community, it is only (to our knowledge) some few companies that have established simulation tools that actually are in use. The reason for that is that simulation tools are only as valid as their input parameters and the current scientific studies suffer from limited knowledge regarding the validity of the input parameters which are used to date. E.g., previous studies have provided a range of values for the kinetic coefficient of kinetic friction and the air drag-area, but these were not specific for the sports freestyle skiing and snowboard, but rather alpine skiing and cross country skiing, where posture and clothing is different.

However, two recent studies which are part of the overall project here have investigated the air drag and ski/snowboard – snow friction for the inrun and also drag area for airborne postures (Wolfsperger et al., 2021a, Wolfsperger et al., 2021b). The speed that is generated in the inrun and carried into the take-off defines, together with the take-off angle of the centre of mass (COM)-trajectory, the initial conditions for the flight (Wolfsperger et al., 2021b, p. 1082). During flight, air drag and lift and gravity alter the initial velocity vector and define where and at what angle to the surface the athlete will land. The landing velocity and angle to the snow surface define the impact in the landing (Wolfsperger et al., 2021b, p. 1082).

This thesis is a portion of a larger project that aims to establish more valid parameters for use in computer simulation of jump kinematics and kinetics in order to allow practitioners and the scientific community to better predict whether a certain jump design is suitable for specific user groups. Here we aim at establishing parameters for the elite level for both ski and snowboard, and in this thesis, we are researching a specific mechanism that is performed during the take-off, the so called “pop” and its implications for performance and the equivalent fall height (EFH), a variable describing the impact at landing. The pop is a mechanism where the athlete uses body extension and flexion to change the take-off angle, and hence, the velocity vector by either “jumping” or “dampening” at take-off. While it is a well-known phenomenon within the freestyle skiing and snowboarding community, the research on pop is limited and performed on recreational athletes in one study (McNeil, 2012). The range of pop values might not be extendable to the elite athletes, since the characteristics of the population used in that study was not documented and thus, are unknown (Shealy et al., 2010, p. 176; McNeil, 2012). Furthermore, the existing study did not measure pop, but determined it indirectly from the $V_{parallel}$ and jump distance measurements (McNeil, 2012, pp. 4 - 5). Therefore, the aim of this thesis is to 1) characterize pop for World Cup athletes in ski and snowboard of both sex, 2) to assess the significance of pop for performance related factors, such as flight time and rotations, and 3) assess how pop is relevant for the landing impact and EFH, a variable suggested to be related to injury risk (McNeil, 2012, p. 2; McNeil et al., 2012, p. 8; Levy et al., 2015, p. 14).

To assess these aspects, kinematic and kinetic data from a slopestyle World Cup competition in Seiser Alm, Italy was used, where ski and snowboard athletes of both sexes participated and performed jumps on three consecutive jump constructions with similar characteristics. Skiers and snowboarders are two groups that are different because of the physical characteristics of their equipment, the manner the athletes are attached to the equipment and the consequences these have for the range of motion, motor control, perception abilities, etc. Especially having both feet attached to the snowboard might significantly limit the manoeuvrability, balance and capacity to regain balance compared to skiing. Therefore, skiers and snowboarders are considered as two populations, since it is suggested that equipment has a larger impact on performance factors and EFH than sex.

1.1 Research questions and hypothesis

In order to contribute to the facilitation of using simulation and computer models as a tool in constructing safer jumps, the aim of this Master’s thesis is to investigate the athlete’s pop in order to provide valid ranges and to better understand why and how the athlete uses it in order to manipulate their trajectory at take-off to enhance performance and possibly safety. To assess these questions, the performed jumps of the slopestyle World Cup competition in Seiser Alm, Italy were investigated, and the specific research questions are the following:

Q1: “What are ranges of ‘pop’ on typical jumps for elite athletes (women, men, ski and snowboard) competing in slopestyle World Cup?”

1.1.1 Pop and its relation to performance factors

Performance in slopestyle jumps is judged on the factors execution, progression, variety, amplitude of the jump (jump time, distance, altitude above ground etc.) and difficulty, which refers primarily to the number of rotations that are performed during airtime (International Ski and Snowboard Federation, 2021, pp. 12, 15). The two latter aspects, amplitude and difficulty, here simplified as number of rotations, are factors that can be objectivized. We have therefore quantified the number of rotations athletes performed in a jump as a measure of difficulty, and flight time as a measure of amplitude. To generate a large amplitude / flight time it was hypothesised that both pop and $V_{parallel}$ contribute positively to a long flight time (McNeil, 2012, p. 1) . Further, the factors that might allow for a large number of rotations during a flight might be flight time and angular velocity. Angular velocity is generated through an angular momentum and the manipulation of the moment of inertia during flight time. The angular momentum is generated from an angular moment in the take-off. Based on these considerations, we set up a model that describes how long flight time and a large number of rotations are generated (figure 1)

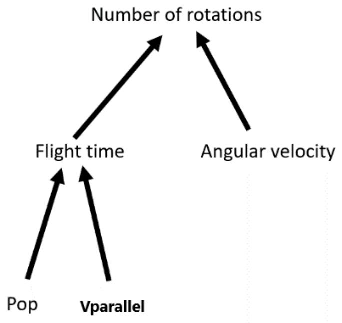

Figure 1: Proposed relationship between the pop and $V_{parallel}$, and the number of rotations an athlete performs in the air.

H1: Higher values of positive pop is related to increased flight time for both skiers and snowboarders in typical jumps in slopestyle World Cup.

H2: Higher $V_{parallel}$ at take-off is related to increased flight time for both skiers and snowboarders in typical jumps in slopestyle World Cup.

H3: Longer flight time is related to a larger number of rotations during flight for both skiers and snowboarders in typical jumps in slopestyle World Cup.

H4: Higher average angular velocity is related to a larger number of rotations during flight for both skiers and snowboarders in typical jumps in slopestyle World Cup.

The angular moment is per definition generated in the plane of the snow surface on the kicker, while generation of pop per definition is generated in direction normal to the snow surface of the kicker. Hence, these two factors, generation of pop and generation of angular momentum, might be independent from each other. However, considering the body extension and rotation initiation motion that is needed to be generated at the same time during take-off, we hypothesize that there is an interaction between generation of pop and angular velocity, and further suggest that a higher $V_{parallel}$ would limit the time athletes have on the kicker to generate both angular velocity and pop (figure 2).

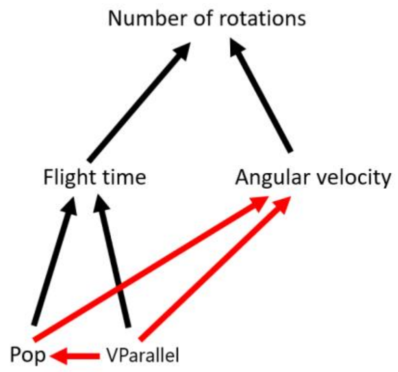

Figure 2: Proposed relationship between the pop and $V_{parallel}$ (VParallel), and the number of rotations an athlete performs in the air (black arrows). In addition to the proposed limiting influence of $V_{parallel}$ on pop and average angular velocity and pop on average angular velocity (red arrows).

H5: Higher $V_{parallel}$ at take-off is related to lower average angular velocity during flight for both skiers and snowboarders in typical jumps in slopestyle World Cup.

H6: Higher $V_{parallel}$ at take-off is related to lower values of pop for both skiers and snowboarders in typical jumps in slopestyle World Cup.

H7: Higher values of pop is related to lower average angular velocity during flight time for both skiers and snowboarders in typical jumps in slopestyle World Cup.

1.1.2 Pop and its impact on equivalent fall height

McNeil (2012, p. 10) found that an increase in pop alters the impact at landing. Extensive pop might lead to longer flight distances and higher EFH for rather uniform landing surfaces. Several studies suggests that the EFH could be related to injury risk (McNeil, 2012, p. 2; McNeil et al., 2012, p. 8; Levy et al., 2014, p. 228) and it is therefore worthwhile assessing the relation visualised in figure 3.

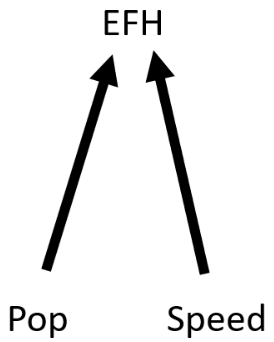

Figure 3: Visualization of the hypothesised relationship between the EFH and pop and velocity parallel to the surface (Speed).

H8: Higher values of positive pop is related to increased mean EFH for both skiers and snowboarders in typical jumps in slopestyle World Cup.

In addition to pop that is changing the angle of the velocity vector at take-off, a higher $V_{parallel}$ will also alter the flight trajectory (Elfmark et al., 2021, p.11) and, for rather uniform landing surfaces, also EFH.

H9: Higher values of $V_{parallel}$ at take-off is related to increased EFH for both skiers and snowboarders in typical jumps in slopestyle World Cup.

2. Theory

2.1 *Freestyle skiing and snowboarding*

Freestyle skiing and snowboarding are modern winter sports that combine high speed, style and showmanship, where athletes are competing against each other by being the fastest down a set course or impressing the judges with their creativity and execution of tricks (The International Olympic Committee, s.a.-a, The International Olympic Committee, s.a.-b). While the sport grew up in the 20th century, it was not until the latter half that the sports' popularity really started to increase, which lead to a development of jump and course designs, equipment and techniques. Since then, the sports have been recognised as disciplines by the International Ski and Snowboard Federation (FIS), which has led the way for varied competitions and events such as World Cup, national cups, Burton U.S. Open, in addition to the highly esteemed XGames (Brettforbundet, s.a.; Bright, 2020). The sports were also recently added to the Winter Olympic Games alongside more traditional winter sports, where freestyle skiing made its Olympic debut in the 1988 Calgary Games and snowboarding in the 1998 Nagano Games (The International Olympic Committee, s.a.-a; The International Olympic Committee, s.a.-b). Both sports have since then made an impact in the world of sports and their subdisciplines are gradually making their debut in the Olympic Games one by one, resulting in freestyle skiing and snowboarding making up a bigger part of the Games.

There are several disciplines that fall within the term freestyle skiing and snowboarding, each with their own niche. While a few of the disciplines value speed and manoeuvrability in heats, others favour creativity, showmanship, and aerial tricks more (The International Olympic Committee, s.a.-a; The International Olympic Committee, s.a.-b). The disciplines are aerials, moguls, ski/snowboard cross, half pipe, slopestyle and big air. While we mainly will investigate the jumps used in slopestyle, we cannot deny that the results could be of value for other disciplines as well, especially big air where manoeuvres are performed over a single bigger jump in similar fashion. Hence, some information regarding big air will also be included.

2.1.1 Slopestyle and big air

Slopestyle and big air are rather modern disciplines that fall within the term freestyle skiing and snowboarding. Common for both are that the athletes compete separately in turn trying to impress judges by showing long flight times, showmanship, style and impressive tricks to acquire a high numeric score. While people had been doing tricks on jumps and rails before, it was then not evident that these manoeuvres would be used as it is in the discipline that would later be known as slopestyle. In competition, slopestyle athletes are competing after each other going down a course separated into sections consisting of rails, jumps or other elements (Bright, 2020; Löfquist & Björklund, 2020; Norwegian Ski Federation, s.a.). In qualification, they have two rounds each, while the athletes that proceed to the finals get two or three additional rounds (depending on the event) to set as high score as possible (International Ski and Snowboard Federation, 2021, p. 70).

In slopestyle, the competition rules for freestyle and snowboard state that the course needs to have at least six sections, in which at least three are jump sections, and that the course allows for the athlete to be able to choose between at least two different lines (International Ski and Snowboard Federation, 2021, p. 71). A guide from the Norwegian Ministry of Culture and Equality (s.a) suggests that three sections of rails or boxes should be followed by three to four jump sections. Slopestyle as a freestyle discipline has currently taken large development steps in short time. It was introduced in the Olympic Games in 2014 in Sochi, Russia and has since then been a permanent component of the Winter Olympic Games for both 2018 in Pyeongchang, South Korea and 2022 in Beijing, China (The International Olympic Committee, s.a.-a, The International Olympic Committee, s.a.-b).

Big air is different from slopestyle in one distinct way. While slopestyle athletes compete trying to tie different sections with different elements together to make an overall good impression to the judges, the runs in big air consist of only one big jump where the athlete have to impress the judges with impressive tricks and flight time to set a high score. In big air the competitors have three attempts/runs to set their scores, in which the two best runs (that does not contain the same trick) will be counting for a combined score that decides a winner (International Ski and Snowboard Federation, 2019, p. 19; Norwegian Ski Federation, s.a.-a). As with slopestyle, big air also just recently entered the Olympic scene, with snowboarders being allowed to participate for the first time in the 2018 Pyeongchang Olympic Games, while big air skiing was an Olympic discipline for the first time in the 2022 Beijing Games (Löfquist & Björklund, 2020; Martínková & Parry, 2020; The International Olympic Committee, s.a.-b)

2.1.2 Scoring

Performance in both big air and slopestyle is determined based on subjective scoring from judges that are very familiar with these sports, typically having a background as athlete, coach, course builder and alike and they are typically active part of the sport community. When judging a competitor, the judges are to set a score to the competing athletes' runs based on different criteria. The official Judges Handbook for Snowboard & Freeski state that "The overall composition (flow) of the run is very important as the judges evaluate the sequences of tricks, the amount of risk in the routine, and how the competitor uses the course" (International Ski and Snowboard Federation, 2019, p. 10). Additionally, mistakes, falls, or other circumstances that might affect the flow, will be taken into consideration and influence the scoring. There exist five standardized objective criteria; Execution, Difficulty, Variety, Progression, and Amplitude, where each encompasses different elements of the runs (International Ski and Snowboard Federation, 2019, p. 10; International Ski and Snowboard Federation, 2021, p. 81). All of these should be considered equal when scoring an athlete. While these are defined criteria items, which are subjectively judged based on the judge's experience, personal preference or course inspection. Hence, athletes doing the same trick can get different scores since the judges' subjective assessment of Execution, Difficulty, Variety, Progression, and Amplitude lead to different performance outcomes (International Ski and Snowboard Federation, 2019, p. 10).

Execution looks at a range of different aspects, and the FIS Judges Handbook list eight different elements a judge might consider when trying to assess the execution; control, take-off, landing, grabs, style, course use, flow, reverts and rails (International Ski and Snowboard Federation, 2019, p. 11). While it covers a lot of different elements, it can be shortly summarized to how well the athlete is able to make each action clean and easy to distinct (e.g., take-off, grabs and landing), chain together the different sections of the course and how well they follow through tricks, actions, and the overall run.

Difficulty refers to how difficult it is to perform the actions of the competing athlete. It is important that the judges have a clear idea of which actions that are more difficult to perform, and that this information is shared among the competition community. There are different parameters one can look at to discern the difficulty; one can look at the number and direction of rotations, how the athlete uses the course (in slopestyle), rail-time and risk taking, to mention a few (International Ski and Snowboard Federation, 2019, pp. 12-13). To be able to judge the difficulty, judges need to make an overall picture of the difficulty of the athlete's runs by combining the elements.

Variety is the criterion that might differ the most between slopestyle and big air, seeing that athletes in big air compete performing tricks in one single jump, whereas athletes in slopestyle chain together tricks in different sections, allowing the athletes to show more variety in tricks, rails, etc. in a single slopestyle run. That does not mean that the judge can neglect variety in big air. Athletes in big air have three attempts, where they count the two best jumps as a total when deciding the final order. The FIS Judges Handbook specifies that these two jumps have to be different, meaning that the athlete has to show some kind of variety to allow for a total score by the judges (International Ski and Snowboard Federation, 2019, p.19). For slopestyle, variety is quite different, since judges assess whether the athlete displays variety in the sense of direction of rotations, tricks, grabs, the elements they use, transitions, take-off / landing orientation in the run that counts for the final result (International Ski and Snowboard Federation, 2019, p. 15).

In the context of freestyle skiing and snowboarding, **progression** mainly encompasses the innovative and creative part of the sports. Therefore, it is reasonable that a new trick never seen before will be rewarded with a good score for progression. The FIS Judges Handbook states that actions that are seen as new, creative and/or unique in regard to tricks, grabs, line choice, or a combination of these for the level of competition, can be recognized as progression (International Ski and Snowboard Federation, 2019, p. 16). It is therefore of utmost importance that the judges have some knowledge of the trends and progression of the sports, such that they accurately can reward progression (International Ski and Snowboard Federation, 2019, p. 16).

The fifth criterion is the **Amplitude**. For big air and slopestyle, amplitude does not necessarily only mean that a higher trajectory will lead to a higher score in amplitude. “Judges recognize good amplitude on jumps by appropriate speed and a clean ‘pop’ off of the take-off and a high arc and trajectory through the air to maximize airtime” (International Ski and Snowboard Federation, 2019, p. 15). In ski- and snowboard halfpipe, attempts are made to objectively measure height of jumps, while in big air and slopestyle amplitude is measured subjectively: A good amplitude in a jump is usually characterised by the athletes jumping with a high trajectory while landing their jumps in something often referred to as the “sweet spot”, as it can be safer while still leaving a stronger impression (International Ski and Snowboard Federation, 2019, pp. 14 – 15). In short, the “sweet spot” can be described as the desired landing point for the athlete, where the landing impact is smaller than in other areas of the landing slope (McNeil et al., 2012, p. 7).

With the judging criteria in mind, it is evident that the athletes need to constantly reach for new heights in regard to tricks and jumps to set high scores and keep up with the competition. This notion is also supported by Löfquist & Björklund (2020, p. 1564) and Parmar & Morris (2019, p. 3), who state that there will always exist a component that will make the athletes push the sport further by doing what no one else has done before. With higher jumps, the speed which must be absorbed in the landing will increase, which is suggested to be related with injury risk (Levy et al., 2015, p. 7; Soligard et al., 2015, p. 28). The worry of the number and severity of injury situations in freestyle skiing and snowboarding are also shared by others, as the number and severity of injures already are among the worst in winter sports (Flørenes et al., 2010, Flørenes et al, 2012; Henrie et al., 2010; Soligard et al., 2015; Soligard et al., 2019). In other words, as the criteria for accumulating points and the athlete’s drive will push the sports further, it is important to assess the injury situation and come up with preventive measures that reduce the risk of injury, while avoid limiting the development of the sport to new horizons in terms of higher scores.

2.2 Injuries in Olympic sports

For the 2008 Beijing Summer Olympic Games, the International Olympic Committee (IOC) conducted an injury surveillance study as part of their long-term injury prevention project, which since has been conducted for every Olympic Games (Junge et al., 2008; Junge et al., 2009; Soligard et al., 2019). The objective of these studies is to describe the incidence and characteristics of the injuries that the athletes sustain during the Olympic Games in a mission to protect the athletes' health by preventing injuries and making future events safer (Junge et al., 2008, p. 413; Soligard et al., 2019, p. 1091). In these studies, injuries were defined as "any musculoskeletal complaint newly incurred due to the competition or/and training during the tournament that received medical attention regardless of the consequences with respect to absence from competition or training" (Junge et al., 2008, p. 414). While the definitions of injuries vary a lot, this consensus derives from a consensus that was reached in football studies at the start of the 21st century and has since been used in a wide range of studies looking into the sports injury problem (Fuller et al., 2006; Junge et al., 2008; Engebretsen et al., 2010; Major et al., 2014; Soligard et al., 2015; Soligard et al., 2019). Furthermore, the severity is expressed by how many days of training/competition the athlete will miss because of the injury, where an injury estimated to cause an absence for more than one week was considered severe (Soligard et al., 2015, p. 442).

2.2.1 Epidemiology

While the incidence rate of injuries varied a lot between the different events in the Winter Olympic Games, the incidence rate of athletes sustaining an injury during the 2010 Vancouver Games in any of the sports was >11%, and 12% during both the 2014 Sochi and 2018 PyeongChang Games (Engebretsen et al., 2010, p. 774; Soligard et al., 2015, p. 442; Soligard et al., 2019, p. 1085). Among all the events, freestyle skiing and snowboarding were among the events that had the highest incidence rates during the Games. While around two thirds of injuries were observed to be of a low grade of severity, resulting in no time loss from the sport, freestyle skiing and snowboarding disciplines were among the events with the highest amounts of severe injuries (estimated time loss from sport >7 days) (Soligard et al., 2015, p. 447; Soligard et al., 2019, p. 1087).

A study performed by Torjussen & Bahr (2006, pp. 230 – 231), aimed to assess the injury pattern in snowboarders at elite level, where the incidence was expressed as the number of time-loss injuries per 1000 runs. By interviewing 228 FIS World Cup competitors in half pipe, big air, snowboard cross, parallel giant slalom, and giant slalom, they found that the number of acute injuries occurred evenly between training and competition. The incidence of injuries for all FIS disciplines in total was observed to be 1.3 (CI95: 1,0 – 1,7) per 1000 runs, where the incidence in big air, snowboard Cross and Halfpipe was observed to be the highest, at 2.3 (CI95: 0.9 – 3.5), 2.1 (CI95: 1.2 – 3.0) and 1.9 (CI95%: 1.1 – 2.8) respectively (Torjussen & Bahr, 2006, p. 232). Torjussen & Bahr (2006, p. 232) adds that it is possible that these numbers could be downplayed as a result of the possibility of recall bias, where the number of smaller, less significant injuries might be under-reported or "forgotten" by athletes and coaches. Out of the 135 acute injuries that occurred, 38 of them caused the athlete to be absent from the sport for over 21 days (Torjussen & Bahr, 2006, p. 232). A few years later, Flørenes et al. (2010, p. 803) assessed the injury situation among World Cup freestyle skiers. Similar to Torjussen & Bahr (2006), Flørenes et al. (2010, pp. 803 – 804) performed interviews of 662 World Cup athletes at the end of the 2006 – 2007 season, 2007 – 2008 season and 2008 – 2009 season. In total, 291 acute injuries occurred among the athletes during these seasons, where around a third (31,3%) of the injuries resulted in a time-loss of over 28 days (Flørenes et al., 2010, p. 804). The incidence rate was observed to be as high as 44.0 (CI95%: 38.9 – 49.0) per 100 athletes (Flørenes et al., 2010, p. 805). It is evident that the risk of injury in freestyle skiing and snowboarding is high.

In order to compare and assess the injury situation in and between different snow sports, Flørenes et al. (2012, p. 58) interviewed World Cup 2121 athletes in alpine skiing, freestyle skiing, snowboarding, ski jumping, Nordic combined and cross country skiing in the winter seasons of 2006 – 2007 and 2007 – 2008. The incidence was described as the number of injuries per 100 athletes, and for the 421 snowboarding athletes, the incidence was observed to be 56.3 per 100 athletes (CI95%: 49.1 – 63.5) (Flørenes et al., 2012, p. 61). Following the snowboarding disciplines, freestyle skiing and alpine skiing had the second and third highest incidence rates, at 38.5 (CI95%: 32.5 – 44.4) and 36.7 (CI95%: 31.5 – 41.9) respectively (Flørenes et al., 2012, p. 61). When looking at the time-loss following the injuries as well, these three disciplines still ranged the highest, and the incidence rate was 11.3 (CI95%: 8.4 – 14.2), 14.4 (CI95%: 10.8 – 18.1) and 13.8 (CI95%: 10.2 – 17.3) for severe injuries (over 28 days absent) for alpine skiing, freestyle skiing and snowboarding respectively (Flørenes et al., 2012, p. 61). Flørenes et al. (2012, p. 58) stated that "1/3 of the World Cup alpine, freestyle and snowboard athlete sustain a time-loss injury each season, while the risk is low in Nordic Disciplines", ultimately supporting the hypothesis that the amount and severity of the injuries in these sports are among the worst in winter sports.

For the 2014 Sochi Games, the rate of injury in slopestyle was 37 (per 100 athletes) for the 46 snowboarders and 30.8 for within the 52 skiers (Soligard et al., 2015, p. 442). For the snowboarders, 70% of injuries in the 2014 Sochi Games were estimated to cause the athlete to be absent from the sport for at least one day, while approximately 30% were estimated to be of severe nature (Soligard et al., 2015, p. 443). The severity of the injuries for skiers seemed to be a bit milder, where 'only' 6 out of the 16 injuries were estimated to keep the athlete away from training or competition for at least a day (Soligard et al., 2015, p. 443). Additionally, 25% of the injuries was estimated to be of severe nature (Soligard et al., 2015, p. 443). In 2018, the injury incidence was 21.2 per 100 athletes (21.2%) for the 66 participating snowboarders and for the 54 skiers, just over 16 per 100 athletes (16.7%) (Soligard et al., 2019, 1087). When looking at the severity, close to 71.4% of the snowboard-injuries were estimated to make the athlete be absent for at least one day, and 50% of the injuries were of severe nature (Soligard et al., 2019, supplementary appendix 1/p. 1087). Again, skiers seemed to have a lower number of severe injuries, where a third of the injuries would cause absence over one day, and around 10% being of severe nature (Soligard et al., 2019, supplementary appendix 1/p. 1087). Big air also debuted in the 2018 Pyeongchang Games for snowboarders, and Soligard et al. (2019, supplementary appendix 1/p. 1087) found an incidence rate of 11.6 per 100 athletes, where 75% of the injuries were estimated to cause an absence of more than one day and 25% of the injuries being severe.

Looking at differences in injury incidences between sex/gender, Steenstrup et al. (2014, p. 43) found differences between sex in head injuries, and observed that the risk ratio between female and male athletes were 1.63 and 1.93 in freestyle and snowboarding respectively. Additionally, Soligard et al. (2015, p. 442) report that the relative risk of a female athlete sustaining an injury compared to male athletes were three times higher (relative risk = 3) in slopestyle skiing during the 2014 Sochi Winter Olympic Games. There were, however, no differences found between men and women in any of the other freestyle skiing or snowboarding events during either the 2014 Sochi or the 2018 Pyeongchang Games (Soligard et al., 2015; Soligard et al, 2019). Additionally, Torjussen & Bahr (2006, p. 231) found no differences between male and female athletes when performing interviews to investigating the injury incidence of snowboarders.

In the study of Flørenes et al. (2012, p. 62) where injuries were compared between different World Cup disciplines, contusions, joint dislocations and fractures were the most common injuries for snowboard athletes, making up 17.6%, 38.6% and 17.6% of the injuries sustained during the 2006 – 2007 and 2007 – 2008 winter World Cup seasons. For freestyle skiers, the number of contusions was a bit lower. However, the two most common types of injuries were still fractures and joint-related injuries, making up 21.7% and 43.3% of the injuries (Flørenes et al., 2012, p. 62). When looking at the body parts that were more commonly exposed to injuries, the knee was the body part where most of the injuries occurred, totalling 29.3% of the injuries for skiers, and 18.9% for snowboarders (Flørenes et al., 2012 p. 62). Other body parts that often were injured was head/face (skiers: 12.7%, snowboarder: 12.9%), shoulder/clavicle (skiers: 10.2%, snowboarders: 13.3%), and lower back/pelvis for snowboarders (10.3%). This could suggest that the knee might be one of the more exposed body parts to injuries within freestyle skiing and snowboarding. This notion is further supported by the findings of Torjussen & Bahr (2006, p. 232), who found that the knee was the most injured body part in big air, making up 6 out of the 20 injures registered. When assessing the injury situation at the winter Olympic Games, Soligard et al. (2015) and Soligard et al. (2019) presented numbers regarding what kind of injury it was and which body parts that were affected by the injury. In slopestyle skiing and snowboarding in the 2014 Sochi Games, there were a total estimation of 9 severe injuries, where the injuries were classified as ligament sprain/rupture (knee), fractures (face and ankle), joint dislocations (shoulder or elbow), concussion, and contusion (Soligard et al., 2015, pp. 442 – 443). In the 2018 Pyeongchang games, injuries included fractures, dislocations, concussion, damage to cartilages and contusions (Soligard et al., 2019, p. 1088).

2.2.2 Cause and mechanisms of injuries

Injury rate and severity in big air and slopestyle are obviously high. However, the sports are popular and primarily young people enjoy these sports on recreational and competitive level, since the reasons and benefits of doing sports are multiple (van Mechelen et al., 1992, p. 84; Bahr & Krosshaug, 2005, p. 324; Soligard et al., 2015, p.441). While most sport injuries have a low grade of severity, the consequences can be diverse and affect several parts of an athlete’s life, such as losing time from work, the sport, and ultimately pose a threat to their lives (van Mechelen et al., 1992, p. 92; Engebretsen et al., 2010, p. 774; Soligard et al., 2015, p. 441; Willmott & Collins, 2015, p. 1247). It is therefore critical that assessment of the situation and aspects of the sports that lead to injuries and figuring how to best prevent them is important.

The predominant situation that caused injuries in slopestyle in the 2014 Sochi Olympic Games was contact with the ground (including features part of the course), while in the 2018 PyeongChang Olympic Games was connected to the features that facilitated aerial movements, such as jumps (Soligard et al., 2015, p. 443; Soligard et al., 2018, p. 1090). Ehrnthaller et al. (2015, pp. 113, 117) found that the injuries of freestyle snowboarders (halfpipe, slopestyle and big air) were predominated by injuries to the knee and the wrist primarily caused by falls on jumps, when the athlete was 1) unable to withstand the strong load in the landing and /or 2) instability in the landing made the athlete fall. This puts emphasis on jumps, and especially the landing, and could suggest that they might be one of the major causes of injuries. When registering injuries in retrospective interviews with elite big air snowboarders, Torjussen & Bahr (2006, pp. 230, 232) found that injuries were caused by falling when landing. This is in line with results from other literature, where it was found that the “disciplines where jumping is a key element (BA, HP and SBX) had a higher injury rate than the alpine disciplines without jumping” (Major et al., 2014, p. 21), where BA is big air, HP is half pipe and SBX is snowboard Cross. Additionally, more knee injuries occurred in these disciplines, ultimately strengthening the hypothesis that knee injuries can be attributed to jumping (Major et al., 2014, p. 4). Ehrnthaller et al. (2015, p. 117) explain that the knee, and more specifically the ligaments in the knee, could be more exposed to injuries as the load in the landing is too much to withstand, resulting in ruptured or destroyed knee ligaments. This suggests that the landing in jumps is one of the events that exposes the highest risk for elite athletes to sustain an injury in slopestyle and big air, and it should therefore be investigated how it is possible to mitigate this risk.

Tarazi et al. (1999, p. 177) assessed the mechanisms behind spinal injuries at two ski areas in British Columbia, Canada. The results from this study showed that collisions in falls and jumps were the predominant causes of the injury incidence of the study, where falls were defined as incidents “involving a jump of less than 2 meters height or a loss of balance for any reason, and a collision as an impact” (Tarazi et al., 1999, p. 178). Out of 22 registered snowboard injuries, 77% of them were related to intentional jumps larger than two meters, while 20% of the skiing injuries were related to jumps. The main reasons for skiers were falls (59%), primarily including jumps and collision with other people or static objects. These numbers seem to agree with the results from Ogawa et al. (2009, p. 535) who found that falls, jumps and collisions were the main reasons of injuries in snowboarding. Ogawa et al. (2009, figure6/p. 535) also observed that the mechanisms seem to differ between the different skill level of the snowboarders, where “experts” more rarely get injured due to falls or collisions, but landing in jumps could pose an increased threat.

Levy et al. (2015, p. 228) pointed at the forces athletes must absorb in the landing as one of the main explanations to why the landing could be associated with injury risk. In order to quantify the forces an athlete was exposed to in the landing, Löfquist & Björklund (2020, p. 1567) used pressure insoles in athletes’ shoes and found that the forces exposed onto the athlete in the landing was about 2 times their own bodyweight. The forces acting on an athlete in the landing are related to the impact velocity and the shape of the landing area and can be described with several models. One perspective is the impulse momentum law (Sternheim 1991, p. 177). The product of velocity times the athlete’s mass is the momentum that needs to be absorbed by the impulse, the time integral of force that act on the athlete over time in the landing as described in Equation 1, where Δv_N is the component of velocity normal to the landing surface, m is the athlete’s mass, F is the Ground Reaction Forces (GRF) that impact the athlete in the landing, and t is the time it takes from the athlete hits the ground to the vertical velocity equals zero.

$$\int F \cdot dt = \Delta v_N \cdot m \qquad \text{(Equation 1)}$$

By dividing the momentum by the time from the athletes touches the ground until the momentum is absorbed, we can calculate the mean force that acts on the athlete in the landing (Equation 2).

$$F = \frac{\Delta v_N \cdot m}{t} \qquad \text{(Equation 2)}$$

Since the athlete’s mass is constant, it is hence, the impact velocity that needs to be absorbed and the time that determine the landing forces. The shape of the momentum absorption force curve and duration of the momentum absorption might to some extent be determined by the length of the athlete’s limbs and their inner factors (such as strength) and motor control. Since the component of the velocity vector normal to the landing surface is hard to relate to a quantitative measure, the component of the velocity vector normal to the landing surface is usually expressed as EFH. Equivalent fall height represents the impact as the height an athlete would fall vertically onto a horizontal surface in order to absorb the same amount of forces an athlete absorbs when landing jumps (McNeil, 2012, p. 10). This can be described for a jump with landing surface and flight trajectory by equation 3

$$EFH = \frac{v_J^2\, sin^2(\theta_J - \theta_L)}{2g} \qquad \text{(Equation 3)}$$

where v_j is the jumper’ velocity vector in the landing, θ_J is the angle of the athlete’s trajectory at landing to the horizontal, θ_L is the angle of the snow surface slope to the horizontal, and g is gravitational acceleration (usually referred to as $9.8 m \cdot s^{-2}$), and EFH is the equivalent fall height.

The conversion of potential energy to kinetic energy for a falling object might help to understand how impact velocity and EFH are related (Equation 4)

$$mg(EFH) = ½\, mv_N^2 \qquad \text{(Equation 4)}$$

where m is athlete’s mass, g is gravitational acceleration, EFH is equivalent fall height, and v_N is the vertical velocity. Hence, EFH and the conversion of potential to kinetic energy during falling might help to relate the impact velocity to a measure (EFH) that one can relate to. However, it is important to point out that EFH is not corresponding directly to height from which the athlete is falling from the highest point of an athlete's arch and the landing point, since the angle between athlete trajectory and landing surface play an important to role in determining the velocity component that acts normal to the landing surface (Equation 3). The smaller the difference between landing and surface angle the smaller EFH will be for a given speed (Hubbard, 2009, p. 178; Böhm & Senner, 2009, p. 173).

In order to provide a guideline for how much EFH a trained human body might withstand, Minetti et al. (1998, p. 1789) found that the maximum vertical drop height an elite athlete can absorb is close to 1.5 metres. This would therefore be used as a reference limiting value for EFH to be used in the landing jump design (McNeil et al., 2012, p. 8; US Terrain Park Council, 2017, as cited in Petrone et al., 2017, p. 290). While 1.5m is considered to by the maximum "safe" values, injuries have been observed to occur in landing jumps that have lower EFH values than this, suggesting that also smaller recommendations than 1.5m could be required (Scher et al., 2015, pp., 75, 80 - 83). Based on these guidelines, Petrone et al. (2017, p. 291) investigated whether it is possible to design and build jumps with a constant EFH, controlling the landing impact. Using three-axis accelerometers on the jumper and equipment, they were able to calculate the EFH and found that the measured EFH was close to the set EFH attempted in the design process, suggesting that jump construction can be used to control the impact in landing (Petrone et al., 2017, p. 291).

2.2.3 Injury prevention models

Different models are deployed to understand the reasons for why injuries occur and what can be done to reduce their occurrence and severity. Bahr & Krosshaug (2005, p. 324) suggest that acute injuries are caused by a single triggering event, while the athlete's internal factors might predispose the athlete for a triggering event to occur. In other words, weaker inner factors can be seen as one of the mechanisms that predispose an athlete to injuries, as the athlete for example is unable to withstand the outer forces at impact. The causes of injuries, however, can also be attributed to external factors, such as course design.

A model that is widely used in the prevention of sport injuries is Van Mechelen's "Sequence of Prevention". This model consists of four steps situated in a loop, which are: 1) assessing the extent and severity of the sports injury problem within the sport, 2) assessing the causes and mechanics involved in the injuries, 3) introducing preventive measures, and 4) assessing the effectiveness of the implemented preventive measures (van Mechelen et al., 1992; van Tiggelen et al., 2008). Ideally, this sequence loops in iterations until the athlete's safety is improved, by the assessment of the number and severity of injuries, followed by the assessment of the mechanisms leading to increased risk of injuries and introduction of preventive measures, and reassessment of injury numbers and severity. The present master thesis is part of the IOC Injury and Illness prevention framework and is following the van Mechelen model and is part of step 2 and 3, where reasons for injuries are assessed and preventive measures are developed and suggested. Ettema (1992, as cited in van Mechelen et al., 1992, pp. 92 - 93) introduced a stress – capacity model, where the stress is caused by external factors and the capacity is fed by internal factors. The prevention of injury is related to the balance between the external stress and the internal capacity of the athlete. There are factors that are more or less impossible to change, also called unmodifiable factors. Such factors are to be seen as challenges that need to be overcome while the focus of the athlete should lay on the factors athletes actually can change. To make the athlete less prone to injuries, it would therefore be beneficial to either increase the athlete's capacity or to reduce the external stress /external factors. With respect to big air and slopestyle landing this would for example be to increase the athlete's capacity by making the athlete better prepared to withstand the external forces they are exposed to in the landing. Inner factors, such as strength, anthropometry, motor control, etc. can prolong the absorption time and reduce the forces to reduce the velocity component that is normal to the landing surface to zero and reduce the maximal force in the landing. Increased muscular strength and better perception, anticipation and motor control might also allow tolerating higher forces in the landing and avoid falls and injuries.

Another way to improve the balance between stress and capacity is by reducing the stress due to external factors. On the example of the jump landings, this would relate to the reduction of the impacts on the athlete in landing jumps. Hence, altering the jump design to influence the take-off and landing conditions might be a way to reduce the landing velocity as an external stress factor (Carr, 1997, p. 74).

It has been questioned whether it is possible to obtain standards regarding the jumps in terrain parks following rider and snow variations, and thus whether computer design models can assist in constructing safer jumps (National Ski Areas Association, 2008, as cited in Hubbard & Swedberg, 2012, p. 77). In order to investigate this assumption, Hubbard & Swedberg (2012, pp. 84 – 90) explored a range of "uncontrollable factors" (take-off velocity, snow melt, friction coefficient, pop, etc.) and how EFH might change following changes in the factors separately (one factor tested at a time, the other parameters are kept constant). Based on their results, Hubbard & Swedberg (2012, pp. 75, 91) concluded that designing jumps using analytical methods for increasing safety of jumps was still viable as the factors either had negligible influence on the EFH, was irrelevant for the design and EFH or could be included in the construction process. Hence, it is suggested as a third step of the van Mechelen's preventive cycle to use computer simulation of jumps to calculate how jumps can be build limiting the EFH, while still allowing for the athlete's creativity (Soligard et al., 2019, p. 1091). Previous projects have already shown that computer simulation is a suitable tool to assess the effect of different jump designs in regards to variables suggested to associate with safety. It was for example observed that the use of computer simulation allowed to estimate the EFH by using kinematic information recorded on athletes (Böhm & Senner, 2009; McNeil & McNeil, 2009).

2.3 Jump Construction/Snow Park modelling

Jumps in recreational snow parks and for competitions are built by practitioners that use their own experience and experience shared between practitioners within the park builder community. While jumps in some sports like ski jumping are standardized to a certain extent, there are no standards in slopestyle and big air. According to a guideline for designing snow parks published by the Norwegian Ministry of Culture and Equality (s.a.), there are mainly four different types of jumps that are used when constructing jumps in terrain parks with different characteristics: the roll-over, the step-up, the table-top, and the step-down. It is further stated that "each of these designs influence the user experience, user safety, construction and maintenance in different ways" (Norwegian Ministry of Culture and Equality, s.a.). The roll-over and step-up jumps can be recommended for all levels of athletes depending on their designs, while table-top mainly are recommended for experienced and up, and step-down only being categorised as an advanced jump (Norwegian Ministry of Culture and Equality, s.a.).

Characteristics for the roll-over is that they are considered as both safe and exciting as they don't limit the athlete's manoeuvrability. They can be recognised by a deck formed as an arch, with the top of the deck being approximately the same height as the take-off point, as can be seen in figure 4a. The step-up is characterized by an arched deck and (start of) landing that are higher placed than the point of take-off that the athlete needs to jump up to (figure 4b). Similar to the roll-over, the step-up is considered as one of the safter jumps. However, it is considered to limit the manoeuvrability somewhat due to a shorter flight time and having to end the manoeuvre earlier (Norwegian Ministry of Culture and Equality, s.a.). The table-top is characterised by a deck that is flat following the take-off (figure 4c). This is usually as high as the point of take-off or slightly lower. While the jump is considered relatively safe, landing on the flat area can make the athlete absorb more forces in the landing. Similar to the table-top, the step-down also has a flat deck, but it is placed lower than in the table-top, as can be seen in figure 4d. The guidelines don't recommend the construction of such jumps following the uncertainty regarding safety (Norwegian Ministry of Culture and Equality, s.a.).

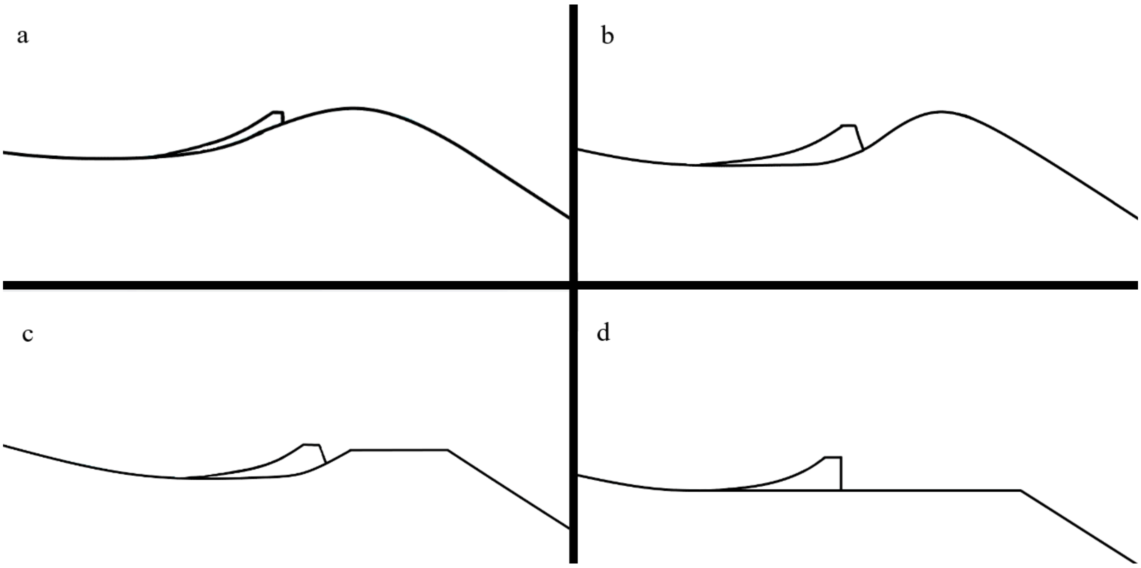

Figure 4: Illustration of the characteristics of the four different jump designs: a) the roll-over, b) the step-up, c) the table-top, d) the step-down.

A vital part of designing jumps is to design jumps that are considered safe to use, while still allowing the athletes to express themselves creatively and innovatively by fitting the different parts of the jumps together (Soligard et al., 2019, p. 1091). As can be seen in figure 5, a jump consists of an inrun, a take-off (often referred to as the kicker), the flight phase/deck and the landing area. Fitting these parts together usually requires experience and knowledge, especially when skiers and snowboarders, men and women all should compete on the same jumps. This is desired also in international championships since jump construction is expensive, such as in the Olympic Games. Hence, jumps are typically to be fitted to athletes of ski/snowboard, men/women, and athletes of different skill levels and seldom to a specific group. McNeil et al. (2012, p. 19) explain that it is possible to use a computer model to aid in jump construction, seeing that it is possible to simulate jump kinetics and kinematics using a computer model. E.g., Böhm & Senner (2009, pp. 172 - 173) calculated EFH using the take-off velocity vector and information regarding the kicker and landing shape. The validity of such type of simulation is only as good as its input parameters. For the time being, it is questionable whether the validity of the input parameters in such simulations is good enough, considering that there exist a wide variety in the input jump parameters. Furthermore, some of the data are obtained on recreational athletes (McNeil, 2012), suggesting that it is difficult to ascertain whether they are of any value when creating jumps intended for elite athletes to use. Elite athletes have been observed to perform more spectacular tricks and higher altitude above ground, as well as showing a different pattern when it comes to injury mechanisms (Ogawa et al., 2009, p. 535; Torjussen & Bahr, 2006, p. 234). It is therefore of importance to find and provide valid ranges of input parameters into such simulations for all groups including elite athletes.

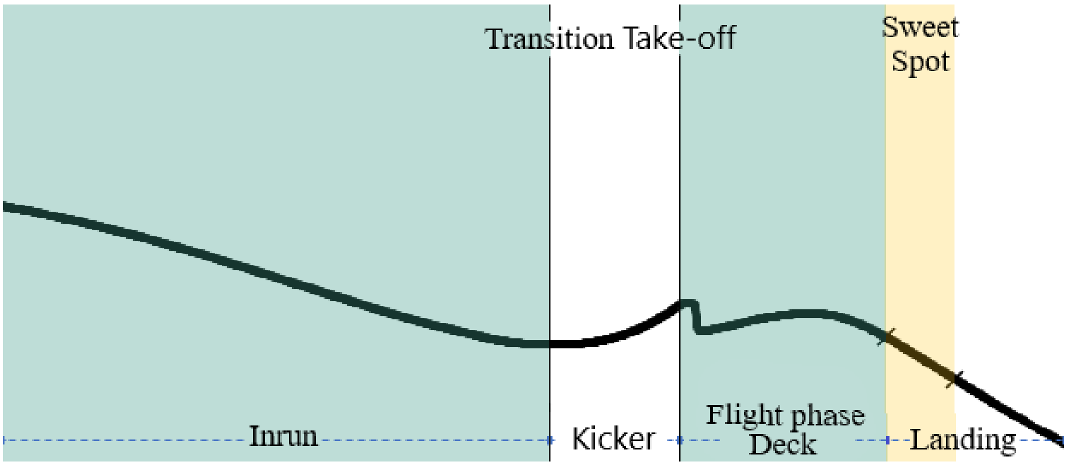

Figure 5: Profile of the first jump section in the competition course in the 2018 Slopestyle World Cup in Seiser Alm. The jump's inrun, kicker/take-off, flight and landing phase are defined, in addition to the spots of transition between inrun and kicker, the take-off (the point where the athlete leaves the ground), and the desired landing area (sweet spot).

As Wolfsperger et al. (2021b, p. 1082) outlines that jump height, jump length and landing impact initially are determined by the angle and speed at take-off, in addition to the shape of the landing and the forces affecting the athlete while airborne. The velocity at take-off is determined by the conditions and shape of the inrun and hence, the factors influencing jump kinematics and kinetics are multiple and are discussed in the following sections.

2.3.1 Inrun

The first part of a jump is the inrun, and the "take-off speed is regulated by the shape of the inrun, which determines the energy to accelerate the athlete…" (Wolfsperger et al., 2021b, p. 1082). The acceleration is determined by three external forces that are impacting the athlete's speed and motion; the gravity, the air lift and drag, and the ski/snowboard-snow friction (Lind & Sanders, 2004, pp. 77, 78, 85; Schindelwig et al., 2019; Wolfsperger et al., 2021, p. 1082). Gravity will pull the athlete towards the centre of the earth (Sternheim, 1991, p. 65). In normal circumstances, this force is exerted on the athletes at all times. As the athlete rides down a decline and not straight down vertically, the gravity force will accelerate the athlete with a force parallel to the decline, decomposed by the vertical gravity force ($F_{parallel} = F_{gravity} * \sin$ (angle of slope)). The air lift and drag and friction between equipment and snow are considered the braking factors of the inrun and are therefore the forces one need to overcome to be able to be able to accelerate downwards.

Air drag is the product of the drag coefficient, air density, frontal area of the athlete and air velocity (squared) that tangents the athlete, divided by two (Sternheim, 1991, p. 366; Wolfsperger et al., 2021b, p. 1084). Furthermore, the drag coefficient is influenced by factors, such as temperature, the gas constant, velocity, etc., in addition to wind that also can influence the air drag (Schmölzer & Müller, 2002, p. 1061; Lind & Sanders, 2004, p. 89; McNeil, 2012, p. 7). Air drag is therefore a complex variable that encompasses several different factors that will determine the braking force of the drag restricting the amount of speed an athlete might generate during the inrun. However, the "Aerodynamic drag always acts on the skier at some effective point determined by the size and shape of the body area the skier presents to the wind stream." (Lind & Sanders, 2004, p. 129). It is therefore reasonable that the apparel and posture of an athlete might help regulate the influence of air drag on the athletes, a notion supported by

Wolfsperger et al. (2021b, p. 1083). Wolfsperger et al. (2021b, p.1083) performed wind tunnel measurements of four skiers and three snowboarders in order to provide valid ranges of air drag in elite athletes by assessing the air drag while using wide, regular and slim fit apparel, and different inrun- and airborne postures. The poses varied from a low to high inrun postures for skiers, and from middle position to extended, and extended rotated for snowboarders. Results showed that, for skiers, body posture was the factor that had the biggest influence on the drag area (77% variety). Additionally, while they had a smaller influence, apparel and speed could also cause some variation, at 30% and 28% respectively. For snowboarders on the other hand, posture and apparel were the two factors that was observed to influence the drag area the most, being able to cause 21% and 23% of variation respectively (Wolfsperger et al., 2021b, p. 1085). While the posture was the factor that had the biggest influence on the drag area, the influence of apparel was not negligible, and as Wolfsperger et al. (2021b, p. 1087) states, going from slim to wide apparel increased the drag area as much as going from mid to extended posture.

In addition to drag, the air also exerts another force onto the athlete, called the air lift. As Carr (1997, p. 118) states, air lift and drag are two force components that can "combine to produce a resultant force that most commonly pushes upwards and backward, and opposes the motion…" of the athlete. Air lift alone is, however, a force that most often is exerted on an object in an upward direction (perpendicular of the airflow) (Carr, 1997, p. 118; Burkett & Carr, 2019, pp. 158 – 159). Considering that the airflow through the athlete is most likely parallel, or close to parallel, to the surface, this force will "lift" the athlete, reducing the forces being exerted by the athlete onto the surface to a certain extent (depending on the size of air lift). This will ultimately cause a reduction of the braking friction forces seeing that friction is calculated using the forces normal to the surface. In the study of Wolfsperger et al. (2021b, p. 1084), lift areas were observed to be 0.319 +- 0.038 m^2 for skiers, and 0.081 +- 0.008 m^2 for snowboarders, where posture was observed to influence the lift area strongly in skiers with the highest lift areas for when the athlete was in the middle position with their upper body slightly inclined.

"Ski-snow friction is a force that always acts to resist the motion of one object sliding on another" (Sternheim, 1991, p. 68). The friction is mainly a product of two factors: the normal force that presses object sliding onto another (e.g., athlete with equipment on snow) and the coefficient of friction (Lind & Sanders, 2004, p. 172). The coefficient "… accounts for the details involved in the friction process, and those details are many and complicated." (Lind & Sanders, 2004, p. 172). Lind & Sanders (2004, pp. 51, 172, 180) adds that both the conditions of the snow (density, temperature, liquid-water content, and many more) and equipment (type of material that is in contact with snow, equipment preparation, etc.) can affect the coefficient. In other words, it is evident that the conditions of the snow, and the characteristics of the equipment, can have an impact on how large the braking forces from friction will be and ultimately how much force the friction opposes the acceleration generated by gravity. As part of this project, Wolfsperger et al. (2021a, p. 7) investigated the coefficient of friction across different ranges of snow conditions and found that coefficient of friction varied from 0.023 to 0.139 for freestyle skis and was slightly higher for snowboarding. Hence, depending on snow conditions the friction force can vary with a factor of 6 between fast and slow conditions. On spring snow conditions with a high liquid water content low friction might occur in the morning when the snow is frozen and high friction coefficients might occur in the afternoon when the snow is warm and wet. Such changes might impact the speed athletes can reach for a given inrun and might play an important role for safety and performance.

2.3.2 Take-off

The take-off ranges from the transition from the inrun to where athletes leave the kicker. The speed the athletes leave the jump with is to large extent determined by the inrun, but in the take-off, the gravity will also affect the athlete in the kicker/take-off itself. In the inrun, the gravity is accelerating the athlete with a force parallel to the slope. On the kicker, the gravity reduces and regulates the speed of the athlete, depending on the shape and angle of the jump. The point where the inrun slope transitions to an incline, the gravitational forces will reduce the athlete's velocity with a force equal to the decomposed force of gravity parallel to the slope. Hence, mainly due to gravity speed is typically reduced from the transition from the inrun to the take-off on the kicker.

As Wolfsperger et al. (2021b, p. 1082) stated, the jump height and length, and the impact of the landing, is initially determined by the angle and speed at take-off.

While a lot of the speed at take-off is determined during the inrun (and partly reduced depending on the shape of the kicker), the angle of the take-off is heavily determined by the angle of the kicker and partly the athlete's action on the kicker. As will be better described later in this chapter, there is one action the athlete can perform to directly manipulate their take-off angle, the pop (McNeil, 2012, p. 1; Wolfsperger et al., 2021b, p. 1082). In short, the pop is an action performed by the athlete by either pushing or absorbing with their legs to either increase their velocity perpendicular to the take-off surface (McNeil, 2012, p. 1; Wolfsperger et al., 2021b, p. 1082). There is one more factor that plays a role in the take-off, and that is setting the angular momentum. When an athlete wants to perform a trick in the air that include them rotating around their own axis (either mono- or poly-axial), this must be prepared in the take-off. This is done by generating a rotational moment between equipment and snow surface of the kicker to initiate an angular momentum that allows rotations in the air (McNeil, 2012, p. 4). The reason this is performed during the take-off and not while airborne, is that after they have left the ground, the angular momentum stays more or less the same through the flight phase, as they don't have any objects to push against, and the effect from air and gravity are seen as negligible on the angular momentum (Carr, 1997, pp. 72, 75, 80).

2.3.3 Aerial phase

In the aerial phase, the athlete's centre of mass trajectory looks like an arch. The reason for this is that the force of the gravity will pull the athlete towards the earth, while air drag and lift also act on the body (Sternheim, 1991, p. 16). When the athlete takes off from the kicker, their vertical velocity will move their mass away from the ground until gravity has acted long enough until the vertical component of the velocity is zero (at the top of the arch), where the athlete starts falling towards the ground and the vertical velocity starts increasing towards the ground. The higher the vertical distance from the landing point to the highest point on the arch, the higher the vertical velocity component might be. While the athlete is in the air, air drag is also affecting the athlete with a braking force exerted in the same direction as the airflow hitting the athlete (Wolfsperger et al., 2021b). Wolfsperger et al. (2021b, p. 1087) measured the drag area in airborne-like positions while performing a grab and at the vertical inflow from below the equipment. Results showed that the drag areas at 0° (from front) and 180° (from behind) were similar, while it from the sides were higher (Wolfsperger et al., 2021b, p. 1085). However, Wolfsperger et al. (2021b, p. 1087) suggested using 0.44 m^2

as drag area for skiers, and 0.40 m^2 for airborne snowboarders. The drag area due to vertical inflow was 0.635 +- 0.005 m^2 for one of the snowboarders, while a skier had 0.412 +- 0.071 m^2, suggesting that the drag areas due to vertical inflow is higher for snowboarders (Wolfsperger et al., 2021b, p. 1085).

The forces of air lift are also still being exerted on the athlete while in the air, and will still, in most cases, exert a force upwards on the athlete. A higher lift vs drag-ratio was observed to correlate well with performance in ski jumping (Elfmark et al., 2022, p. 5). This notion is also supported by Carr (1997, p. 118), who states that one of the reasons the athlete is able to jump to incredible lengths are because of the lift extending the time they are able to stay in the air. However, as Elfmark et al. (2022, p. 5) explain, while this seemed to be the case in bigger ski jump hills, the correlation was non-existent in the smaller hills. Considering the length and time being airborne in the performed jumps in slopestyle, it is reasonable to assume that it does not have the same effect as in the bigger hills in ski jumping. Wolfsperger et al. (2021, p. 1087) suggested using a lift area of 0.09 m2 for skiers and 0.04 m2 for snowboarders, which would result in a fairly low lift to drag ratio for freeski and snowboard, compared to ski jumping.

In the flight phase, the athlete cannot change their angular momentum, as that is set at take-off. However, the athlete can adjust body posture to control their rate of spin, or angular velocity. The relation for angular momentum with angular velocity and moment of inertia is described in equation 5, where L is the angular momentum, I is the moment of inertia, the athlete’s resistance against rotation, and ω is the angular velocity, the rate of the athlete’s rotation.

$$L = I \cdot \omega \qquad \text{(Equation 5)}$$

If we were to separate the angular velocity, the angular velocity is the quotient of the angular momentum divided by the moment of inertia, suggesting that an increased moment of inertia would reduce the angular velocity, and vice versa. Carr (1997, p. 69) states that there are two main determinants of the inertia; the athlete’s mass and its positioning relative to the axis (e.g., distance). While one of the two determinants of the angular velocity is decided in the take-off, the athlete might alter the angular velocity by increasing or decreasing the distance from their limbs and mass to the axis of rotation.

Hence, an athlete needs to assess their global orientation during spinning while being airborne and change body posture to alter angular velocity in order to perform the manoeuvres and tune the body posture and orientation for a safe landing.

2.3.4 Landing

The landing area is shaped such that athletes can land within a reasonable range from take off without being hurt. During the landing procedure athletes stop the angular momentum, and hence, rotation, and absorb the landing impact. During landing, the athlete is exposed to rather large forces in the landings (Löfquist & Björklund, 2020, p. 1564). As Sternheim (1991, p. 179) explained, it is possible to use the momentum change and impulse to determine the forces that act upon the objects in a collision. Newton's third law state that when an object (e.g., the athlete) exerts a force to another object (e.g., the ground), the other object exerts a reaction force of the same size in the opposite direction back (Sternheim, 1991, p. 58; Lind & Sanders, 2004, p. 8). When an object hits the ground, this force is usually referred to as the ground reaction force (GRF). This means that in the landing, the athlete will exert a force on the ground which will be exerted back on them. In that regard, a higher jump trajectory can be a factor of hazard. In the flight phase, the athlete is pulled towards the ground by the forces of the gravity, and, as Carr (1997, p. 75) clarifies, the linear momentum of the athlete towards the ground is increased as the athlete is accelerated towards the earth. In other words, the higher the difference between the vertical distance of the athlete at the top of the trajectory and the landing spot, the higher forces are exerted on the ground by the athlete and vice versa.

In order to measure the magnitude of the GRF male slopestyle skiers were exposed to in the landing, Löfquist & Björklund (2020, p. 1563) used pressure insoles in the boots of male freeskiers in trial jumps. Results showed that the athlete were subjected to around two times their own bodyweight when landing in the “sweet spot” after performing a 180-degree rotation in the air (Löfquist & Björklund, 2020, p. 1567). The “sweet spot” is considered as the spot or the area in the landing where the landing impacts are the lightest and is therefore considered the desired landing spot (McNeil et al., 2012, p. 7). This spot is usually right after the knuckle (the start of the landing that are usually rather flat in step-down or table-tops) where the angle of the landing surface is more suitable for reducing the force normal to the surface (McNeil et al., 2012, p. 7; Löfquist & Björklund, 2020, p. 1566).

Another measurement that often are used to describe the forces that is exerted on the athlete when they hit the ground is the EFH. As the name suggests, the EFH number represents the equivalent height one must fall vertically from onto a horizontal surface to absorb the same amount of force an athlete needs to absorb in landing a jump (McNeil et al., 2012, p. 6). Equivalent fall height was described earlier and is dependent on velocity and the angle between the trajectory and the landing surface as described in equation 3. “The EFH can be made arbitrarily small by making the angle of the landing surface closely match the angle of the jumper’s flight at landing.” (McNeil et al., 2012, p. 6). This tells us that while the impact of landing is initially decided by the take-off velocity and angle, the angle of the landing slope compared to the athlete’s landing is also a factor that can limit the EFH and the forces the athlete are exposed to in the landing, which could explain why an athlete would want to land in the “sweet spot”.

2.3.5 Pop

In the section take-off, the role and characteristic of the vertical motion called pop that is used to manipulate the take-off angle was roughly described, but since the topic of this master thesis is related to this mechanism more detail is provided here. Shealy et al. (2010) tried to look into the relationship between the take-off velocity and the distance the jumpers jumped. If we consider the angle of the take-off (kicker) to be the same angle for all jumpers, it would be reasonable to assume that there should exist a relationship between take-off velocity and distance (depending on the aerodynamic drag affecting the athlete). However, this was not the case. McNeil (2012, p.1) assessed the Shealy et al. (2010) data and suggested that the alteration of the take-off angle, the pop could be the variable that would explain the lack of correspondence between take-off speed and jump distance. Pop is the action of an athlete using their legs to either pull up (absorb) or extend (jump) their legs just before and at take-off to increase or decrease the take-off angle (Wolfsperger et al., 2021b, p. 1082). Additionally, McNeil (2012, pp. 4 - 5) claims that while the pop can change the take-off velocity, which is mainly done through altering the velocity component perpendicular to the surface, as the low friction only allows negligible change to the velocity vector parallel to the surface. While this is a phenomenon that now is well known within the freestyle community, there is only one study assessing the subject (McNeil, 2012; Wolfsperger et al., 2021b).

In an attempt to quantify pop values, McNeil (2012, p.1) used the results found in Shealy et al. (2010), where a total of 280 jumps were recorded over two different jump setups. A third hypothetical jump was added by McNeil (2012, p. 2) for their study. The three jumps had different designs, where the first jump had a take-off angle (surface) of 26˚, the second 21˚, and the third 25˚. All jumps were categorised as table-top jumps. By using the take-off $V_{parallel}$, the angle of the take-off surface and the jump distance, McNeil (2012, p. 3) calculated velocity perpendicular to the take-off surface (pop) to fit the speed data to the jump distances, and hence, quantify the pop, the velocity component that is normal to the take-off surface (McNeil, 2012, p.5). Results showed that the angle varied from a pop of -14.2˚ to 5.3˚, resulting in a velocity perpendicular to the surface to range from -2.48 m/s to 1.12 m/s over the three jumps (jump 1: -2.48 – 0.83 m/s, jump 2: -0.65 – 1,12 m/s, jump 3: -1.0 – 1.0 m/s), where EFH ranged from 0.01 to 1.64 metres, and an increase in the pop lead to an increase in EFH (McNeil, 2012, p. 8). Furthermore, McNeil (2012, p. 10) stated that that “EFH scales as the take-off speed squared and is roughly proportional to the sine of the take-off angle”. In other words, it is strongly suggested that the pop is a factor that can gravely impact the EFH, and hence, the forces exerted onto the athlete in the landing.

This puts emphasis on the need to better understand the characteristics of pop within freestyle skiing and snowboarding in order to provide aid in jump simulation trying to limit the EFH. In the study of Hubbard & Swedberg (2012, p.88), assessing the influence of different “uncontrolled factors” on the calculated EFH, the absence pop (compared to the assumed maximum conceivable pop of +2.25 m/s) was estimated to substantially decrease the EFH (given that the other parameters stayed constant). Hence, it was suggested that the pop should be included as a parameter when using computer models to construct and design jumps that limit the landing impacts. The study by McNeil, (2012) and Shealy et al. (2010) assessed athletes of unknown gender, performance level etc. and thus, it is impossible to provide specific ranges of pop for specific user groups and types of jumps. Hence, in order to better understand the phenomenon of pop and to provide valid ranges of pop for user groups, it needs to be assessed how pop relates to users, type of jump, and also speed. Athletes might use pop to regulate for overshooting speed or lack of speed by impacting the take-off trajectory by popping. From the previous studies it is expected that pop also influences EFH and jump distance, because this is what athletes aim to regulate with the pop (McNeil, 2012, pp. 3, 11). However, pop might also be related to the generation of angular momentum during take-off, and relation to number of rotations and axis might provide useful insights into the effect of pop.

2.4 Collecting Kinematic data

Motion capture systems are used to collect motion in indoor and outdoor conditions, whereas a wide range of different tools have been proposed over the years, ranging from the optical recording of athletes to wearable tracking technology (Gilgien et al., 2018, p. 1; Ostrek et al., 2019, p. 2). Whereas certain tracking technologies allow to track and represent the athlete only as a point mass others allow the reconstruction of the human being as a segment model. To represent the human being as a segment reconstruction, Spörri et al. (2016, p. 2) state that infrared light stereophotogrammetry is one of the systems when it comes to recording and measuring human kinematic data. It is considered to be the golden standard of collecting three-dimensional (3D) kinematic data in laboratory settings (Ostrek et al., 2019, p. 1). It is therefore most commonly used in laboratory conditions, and it relies on the use of markers connected to the athlete to capture the human motion with the use of a human capturing system (Spörri et al., 2016, p 2). To test whether it would be feasible to bring such a method into the field to gather kinematic data, Spörri et al. (2016, p. 3) set up 24 infrared-cameras that were to record skiers wearing a dedicated suit during one turn on skis. While results showed that the recorded data was very precise, the practical usability was questioned considering the small volume of captures and snow spray obscuring marker detection (Spörri et al., 2016, pp. 8 – 10). Furthermore, one can argue that it would be difficult to record data that would be valid for athletes in their natural setting considering the intrusive nature of the setup (wearing specific suit and the amounts of cameras needed).

As Ostrek et al. (2019, p.2) explain, more recent approaches have used multiple panned/tilted/zoomed video cameras setup to assess the kinematic data in alpine skiing (video-based stereophotogrammetry). Because of its accuracy and precision in 3D human pose estimation, it is considered the golden standard for gathering kinematic data in outdoor conditions (Ostrek et al., 2019, pp. 1 – 2). This method relies on manual annotations and a multiple calibrated cameras from multiple views (unless it is paired with wearable measurement technology), which is complex (Ostrek et al., 2019, pp. 1 - 2). Furthermore, Rhodin et al. (2018, p. 8437) state that manual annotations are slow, tedious and prone to human errors and suggests the use of computer vision to remove this complex and time-consuming part of the analysis. Ostrek et al. (2019, p. 2) investigated whether a computer vision approach was ready for the field by estimating a skiers pose with the use of a single camera and compared the results with the data from video-based stereophotogrammetry. Results were promising, and Ostrek et al. (2019, pp. 11 - 12) argues that such an approach could be judged to be both valid and feasible in gathering kinematic data, despite some compromises to accuracy and precision. For most optic motion capture systems large capture volumes are challenging, since such systems need some sort of image calibration that allows to relate the two-dimensional image to the 3D space. Such calibration is typically conducted through known locations that are within the calibration volume and the image. The larger such volumes are the more complex such calibrations need to be. Since slopestyle courses are several 100m long, an adaptation of an existing motion capture solution will be used that is specialized for large volumes.

2.4.1 QDaedalus motion capture method

To capture athletes in the large volume a specialized method was used that was originally developed to track stars at night in the skies and later adapted to track aeroplanes during landing. QDaedalus is a modified total station system, that primarily was developed for use in astro-geodetic measurements, at the Institute of Geodesy and Photogrammetry at ETH Zurich (Bürki et al., 2010; Guillaume et al., 2012; Charalampous et al., 2015), and the setup can be seen in figure 6. However, while it was developed for use in astro-geodetic measurements, it has been proven to be of use for other purposes as well (Charalampous et al., 2015, p. 92; Link et al., 2021, p. 5). While “normal” video camera measurements usually do not provide 3D-positions directly without a calibration process that includes known landmarks in the image field, the QDaedalus system allows to track 3D position reconstruction without calibration of the image taken from the QDaedalus total stations, and is hence, suitable for slopestyle course tracking and was already proved suitable to track ski jumping (Link et al., 2021, p. 5).

The system uses a Leica total station as its base, where the ocular of the total stations has been swapped out with charge-coupled device (CCD) sensor/chip with a meniscus lens mounted in front of the lens to capture the images in a digital form. The server motors of the total station are connected to a laptop where the current image is shown and the QDaedalus total station orientation is altered with a joystick to follow and track the athlete. Two such stations are set up and both equipped with low-cost GPS systems that are used to time synchronize the two camera systems from the two QDaedalus total stations. Hence, time synchronized CCD camera images are logged together with GPS time and horizontal and vertical angles of the QDaedalus total station (Bürki et al., 2010, pp. 1 – 2). The positions of the QDaedalus total stations are recorded with differential GPS and these positions along with reference points and angle and distance measurement are used to calculate the relative positions and angles between the QDaedalus total stations and reference points. These measures are used along with the video recordings and annotation for the athletes in the image to calculate the 3D position as a forward intersection (Vosselman, 2001, p. 23).

Figure 6: An image showcasing the setup of the QDaedalus Total Station when used in recording athletes in freestyle skiing and snowboarding.

2.4.2 Computer Vision

In short, CV is a method/technology that has evolved substantially over the later years, where a data algorithm is fed data from one or several pictures that is transformed it into a new representation with a specific purpose (Bradski & Kaehler, 2016, p.2). Shapiro (2001) state that "the goal of computer vision is to make useful decision about real physical objects and scene on sensed images" (p. 13). However, unlike most humans, computers cannot directly "read" colour hues. To make the CV-models read colours, the data that is fed to the model comes in the form of a matrix consisting of numbers representing the brightness or the values of red, green, and blue for each pixel (Bradski & Kaehler, 2016, p. 3). Based on this data, the algorithm performs their intended task to produce some output based on their specifications.

For the model to perform their intended task, it is necessary to train the model and calibrate its algorithms to enhance performance for the specific task. Depending on its intended use, there are several ways the model can be trained. One common way is through supervised learning. In supervised learning, the model is fed a dataset consisting of images labelled with true observed values. The algorithms then process the images and predicts an output using these data. This is performed in multiple iterations, where the predicted output and true labelled values are compared in each iteration. The calibration of the algorithms from the iteration where the differences in the predicted and labelled values are the smallest are stored and used in the final CV-model.

Computer vision has a lot of uses, and over the years, several different approaches have been proposed as to assist in solving different sports situations. Thomas et al. (2017) have observed that it already plays a vital role in the world of sports as we know it today, whether it is by assisting in broadcasting, upholding safety standards, or in coaching athletes in technical sports. One of the areas CV has been proposed for, is in gathering kinematic data and human pose estimation (Ostrek et al., 2019; Rhodin et al., 2018; Zhang et al., 2019). "Human pose estimation aims to predict the spatial coordinates of human joints in a given image." (Zhang et al., 2019, p. 3518). Rhodin et al. (2018, p. 8437) proposed a CV approach in order to estimate an alpine skiers pose during a run, which could prove beneficial in biomechanical and performance analysis.

Ostrek et al. (2019, p. 1) further investigated whether such an approach could be feasible in gathering kinematic data in alpine skiing. After training the algorithm using labelled data from several camera angles, Ostrek et al. (2019, p.10) were able to find that the average mean of the differences of the relative COM position was 0.03 +- 0.01 metres between the video-based stereophotogrammetry (golden standard) and the CV approach. The results were very promising, and Ostrek et al. (2019, p. 11) further stressed the superior practicability of such an approach.

It is evident that using a computer vision approach can be very helpful when gathering kinematic data and estimating the pose of the athlete. However, while it could be possible to solve sport problems by applying models trained on labelled data from related, but not sports specific, situations (transfer learning), it is recommended that algorithms undergo training on application-specific data to optimize the performance (Ostrek et al., 2019, p. 12; Parmar & Morris, 2019, p. 1). The reason for this is that training data is harder to obtain in sports (not as much data available, in addition to movements being more uncommon and backgrounds being more complex (Fastovets et al., 2013, p. 1048; Rhodin et al., 2018, p. 8347).

3. Methods

3.1 Participants

The participants in the project were elite athletes either competing in freestyle skiing or snowboarding. In total, there were 179 participants. The distribution of male and female athletes, skiers and snowboarders can be found in *table 1*. Information regarding anthropometrics were gathered from all athletes, but were not used in the current study. All participants were informed about the project and consent were given for their runs to be recorded before the collection of data was initiated. In total, 416 runs were recorded. Each run consisted of three jumps, resulting in 1248 possible jumps.

Table 1: The distribution of participants that are male and female, and whether they competed in ski or snowboard.

	Male (n)	**Female (n)**	**Total (n)**
Ski (n)	68	22	90
Snowboard (n)	58	31	89
Total (n)	126	53	179

3.2 Data Collection

The data was collected over four days during training, qualification, and the final of the 2018 Freestyle World Cup in Seiser Alm, where all classes (male skiers, female skiers, male snowboarders, and female snowboarders) competed using the same course. The course consisted of six sections, where the last three of them were jump sections, as can be seen in figure 7.

Figure 7: Image of the full competition course in Seiser Alm consisting of six sections, in which the three last sections are jump sections.

Collection of athlete kinematics was performed using a QDaedalus surveying method, a tachymeter-based measurement system that was developed for scientific applications by the Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland. Two such systems were set up at two separate locations, approximately 300 metres from the course (figure 8), where both recoded from their own side of the competition course. The view of a station from the course, and vice versa can be seen in figure 9 and 10. Additionally, the snow surface was recorded and mapped using a Leica Pegasus backpack system (Leica Geosystems, Herrbrugg, Switzerland). 3D-wind velocities were recorded at 1 Hz with two ultrasonic anemometers (Model 8100, R. M. Young Company, United States). Snow conditions were also measured, but were not used in the present study.

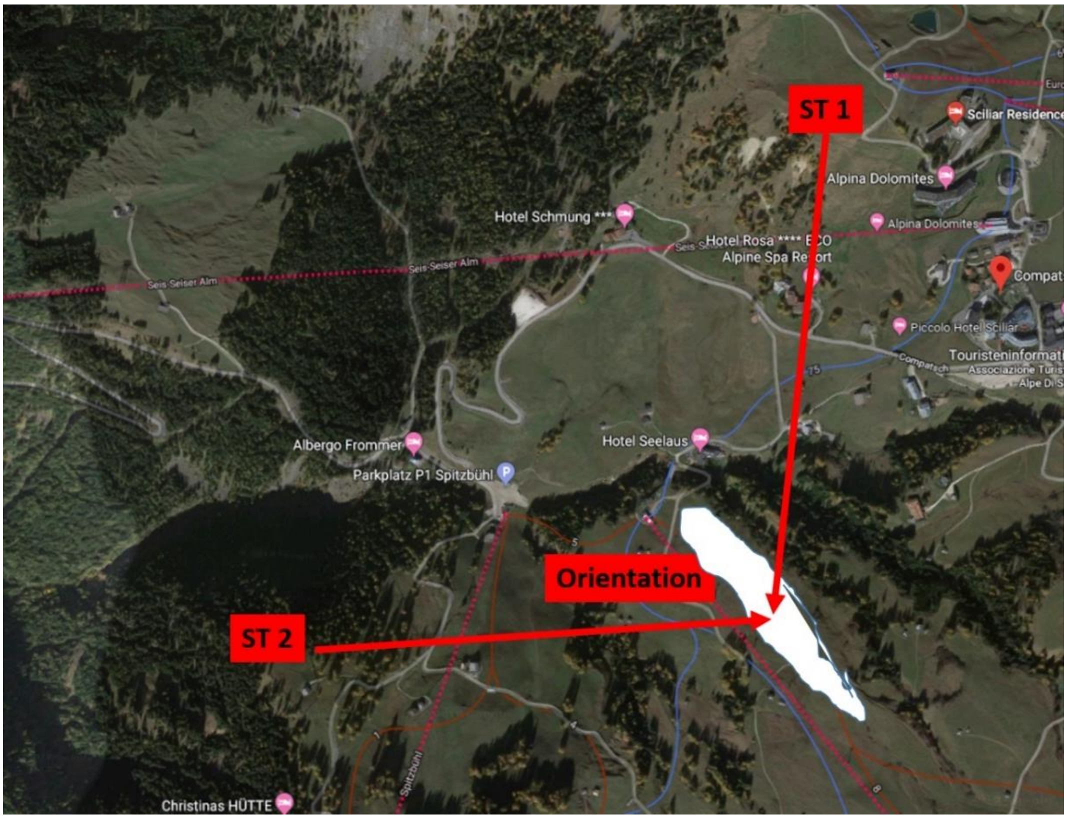

Figure 8: Map of the Seiser Alm area showing the position of the slopestyle competition course (white snow area), and the position of the QDaedalus surveying systems with station 1 (ST1) and station 2 (ST2) and the orientation of the surveying systems (red arrows).

Figure 9: View of the first station of QDaedalus Total Station (QDeadalus Station 1) from the competition course.

Figure 10: View of the competition course from station 2 of the QDaedalus surveying system position. The red frame highlights the slopestyle course.

3.2.1 QDaedalus total station

To record the athlete, the QDaedalus surveying method was used at two separate stations approximately 300 metres from the course (Bürki et al., 2010; Hirt et al., 2010; Charalampous et al., 2015; Link et al., 2021). The base of the QDaedalus system is a Leica (TCA 1800) total station (Leica Geosystems Heerbrugg, CH). The ocular of the total station is swapped out with a charge-coupled device (CCD) sensor/chip, while the meniscus lens was mounted in front of the telescope to negate the optical blur the mounting of the CCD sensor. An adapted CCD camera capable of transferring 30 frames per second, in combination with a low-cost GPS receiver that was mounted on the total station and was used to time synchronize the recordings from the two total stations. Additionally, a focus layout was mounted on the station, allowing remote control of focusing.

The modified total stations were mounted on tripods (as can be seen in figure 6 and 10) and connected to computers that have customized software developed in C++ that was used for database creation, and storage, connecting and matching the data from recordings, and calibrating the CCD sensor. Additionally, the software on this computer was used to take over the server motors in the QDaedalus total station to manoeuvre the horizontal and vertical orientation of the QDaedalus total station during recording. On the screen, the view of the QDaedalus total station was visualized and the joy stick that was connected between computer, total station and the server motors were used to steered the vertical and horizontal angles of the QDaedalus total station while recording the athlete.

One of the advantages of using the QDaedalus, is that when it is recording, it is possible to acquire calibrated pictures containing information regarding the positions of the stations and their recording directions, ultimately allowing calculation of an athlete’s position through forward intersection of the recordings from two or several QDaedalus total stations. First, the two modified QDaedalus total stations were set up at two separate locations 300 metres away from the course (figure 8). Then a third reference position was established in a position that was visible from both QDaedalus total stations (figure 11). After setting up the QDaedalus stations and the reference point, the global positions of these were measured using differential global navigation systems (dGNSS). Angles and distances between the QDaedalus stations and the reference point were measured using the total stations to establish a local network and establish baseline and global orientation for the QDaedalus stations. These were later used to calculate and reconstruct the 3D position of the athlete’s COM-positions. Toth & Volgyesi (2019, p. 77) state that calibration is necessary every time the conditions of the system are changed. In this project calibration was performed at the start of each day and the end of each measurement day and potential drift over time was distributed. However, such changes over time were negligible small in these data collections. During recording, each QDaedalus station was operated by two persons to manually track the athletes on the course. Using the joy stick steering of the server motors the vertical and horizontal direction of the stations was

Figure 11: Reference orientation point was measured with differential GNSS/GPS to establish global orientation for QDaedalus system.

manipulated to track the athlete from both stations throughout the course. The runs were captured with a rate of 30 frames per second. Each image recorded was paired up and stored by the system with the GPS-time of the recording, and the position and direction (horizontally and vertically) of the QDaedalus total station.

3.2.2 Digital terrain model

The slopestyle course snow surface was captured using a LiDAR scanner that was connected to a dGNSS supported inertial navigation system (INS), that connected the Lidar scanning to the global reference frame (Pegasus backpack system, Leica Geosystems, Heerbrugg, CH), Figure 12. The LiDAR scanner sends optical signals in defined directions to the surrounding. This signal is then reflected once it hits an object, and the time it took for the beam forth and back from the object was used to calculate the distance between the system and point of collision. By using the distance, direction and INS position and orientation position of the collision of the point on the surface is represented as position in a global reference frame. The recording personnel wore this backpack as they slowly skied down the slopestyle course, creating a representation of the digital terrain model in a 3D-coordinates system (figure 13).

Figure 12: An operator wearing the Leica Pegasus backpack system which was used to establish a point cloud of the snow surface.

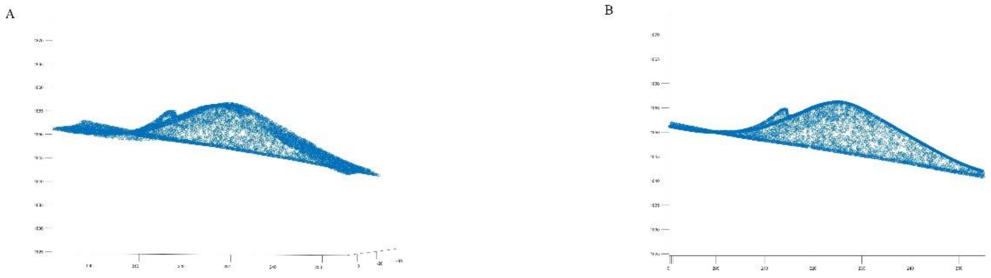

Figure 13: A) Map of an excerpt of the mapped point cloud representing the course profile using the Leica Pegasus backpack in a coordinate system. B) An excerpt of one jump of the transformed course profile using the Helmert transformation.

3.3 Data processing

3.3.1 Image preparation

To analyse the pop, take-off speed and other factors related to the pop, the athlete was reconstructed and represented as a point mass located in the athlete’s COM-trajectory. To reconstruct this position, the recorded images from the QDaedalus stations, the locations, orientations and direction tracking from the QDaedalus stations, and GPS-based time synchronisation information were used. In a first step, the QDaedalus images were prepared to run a CV based approach to identify and annotate the COM-position in each image and both stations. The CV based annotations were corrected manually where necessary. The 3D-position in a global reference frame were then calculated from the QDaedalus station direction measurements of the centre of the image and their adjustments from the image coordinates from the COM annotation. The 3D COM-position reconstruction was conducted using a forward intersection method.

When inspecting the captured images of the athletes, it was apparent that it in multiple runs were difficult to distinguish the athlete from the background while the athlete was in the air (example in figure 14). The reason for this is that everything was recorded in black and white-images, and that there was both a multitude of trees and stones in the background of the course that appeared in the recorded images. In some parts of the runs, it was difficult to separate the athlete from these objects. In order to limit the amount of background noise that could affect the prediction of our CV algorithm and to exclude persons standing along the course to be identified as the athlete in the object identification step, we used the QDaedalus software to put a grey mask over the conflicting and outer parts of the capture volume, as can be observed in figure 14. First, the outer borders were defined based on image and direction information from QDaedalus. After annotating the borders, images containing the grey areas were made multiplied with the original image files, resulting in the images containing a mask of grey at the outer and conflicting parts of the course. This was performed on all data on both stations and used as input data to the CV process.

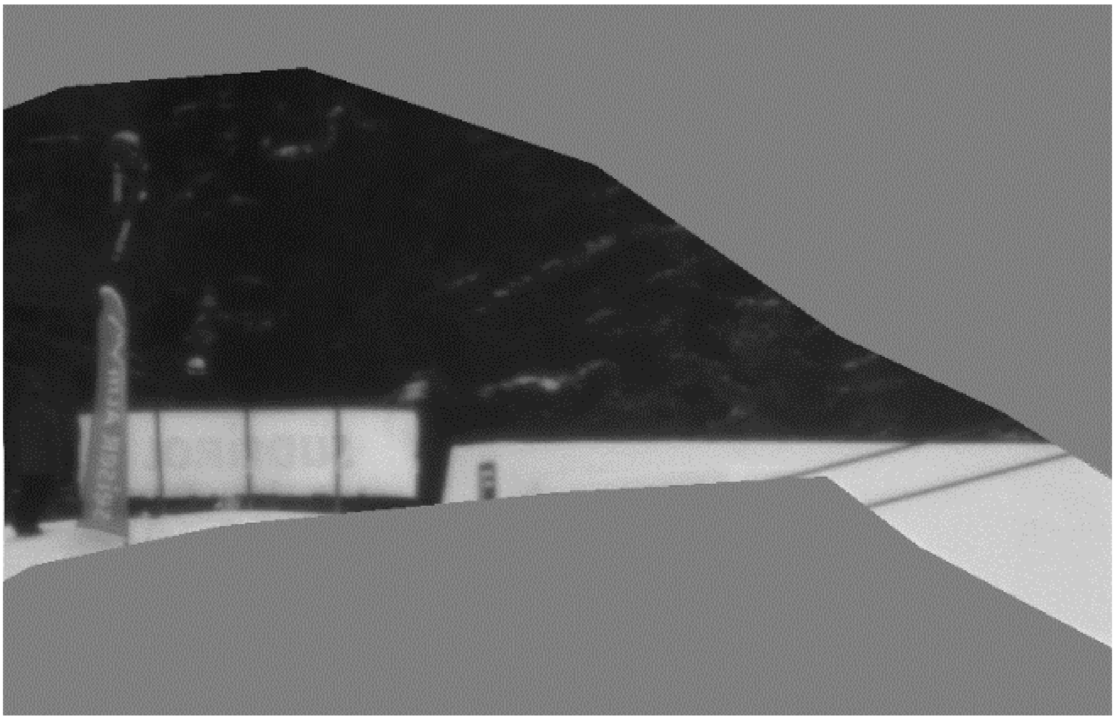

Figure 14: Recorded image where the athlete is front of problematic background. The athlete is positioned in the upper left corner of the image. The one-tone grey areas are the result of masking the outer and conflicting parts not directly interfering with the athlete's trajectory.

3.3.2 Computer vision-based athlete pose estimation

The CV-model we used to automate the annotations process consisted of a feature pyramid network (FPN) (Lin et al., 2017) with a residual neural network (ResNet) that had a backbone of 101 layers (He et al., 2016). The model relied on the implementation in detectron2, a computer vision library that have emerged from Facebook’s AI research that provides state-of-the-art detection and segmentation algorithms (Wu et al., 2019).

The CV-model was trained using the COCO dataset, a dataset available in the detectron2 model zoo, containing over 200,000 images, over 80 object categories for object detection and 250,000 instances of pose estimation of persons in different conditions. While (Ostrek et al., 2019, p. 12) strongly suggested training of a CV-approach on sports-specific data when gathering kinematic data to ensure reliable and valid outputs, we did not perform any sports-specific training on our algorithm and only relied on transfer learning from the COCO dataset containing related CV-tasks. We tested several different approaches, some with no specific training, and others trained with labelled annotated data from our dataset. In theory, training the model on specific data should help increase the validity of the predictions on the dataset, however, there were little-to-no differences in the results of the versions.

Our CV-approach consisted of two separate steps. First, the algorithm tried to predict whether there were any objects in the picture that could be classified as a slopestyle athlete. If it estimated that the object was in the image, a bounding box was set to limit the area in which the athlete might be, as can be seen in figure 15 (red box). Secondly, after the bounding box had been placed around the athlete, another part of the algorithm estimated the pose of the athlete, and annotated the joints of the athlete within this bounding box. In total, 13 joints were annotated (head, right and left shoulder, right and left hand, right and left hip, right and left knees and right and left feet). Based on the position of the joints, the algorithm estimated the limbs by connecting a line between adjacent joints. To find the athlete’s COM, each of the limbs had weights using the Zatsiorsky segment parameter model with the de Leva adjustments (de Leva, 1996), that made it possible to estimate the position of the athlete’s COM. This algorithm performed this process for every single image in every run and the COM and pose estimation data were visually represented in images (as in figure 15), allowing for visual inspection of the algorithm’s performance.

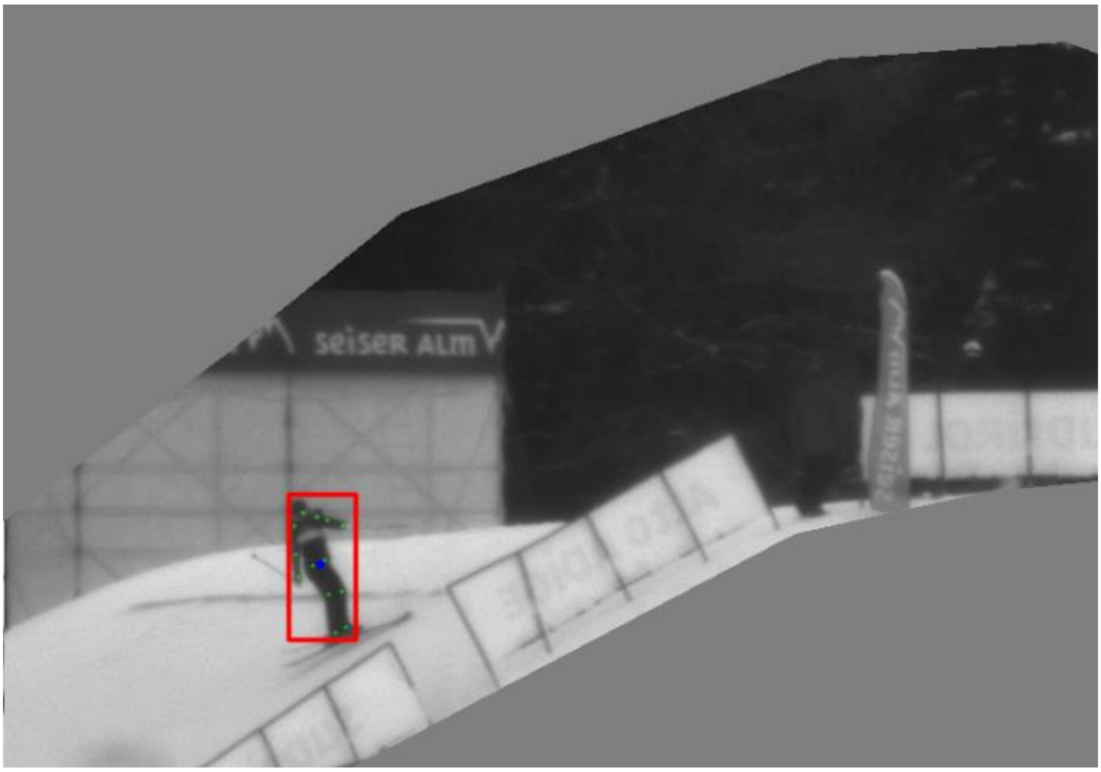

Figure 15: The output of the prediction from the Computer Vision model. The red box represents the bounding box, the green dots the estimated position of joints (pose estimation), and the blue dot represents the calculated COM-position.

3.3.3 Manual corrections of the computer vision output

After running the CV-algorithm the output was inspected and it was evident that it was not able to fully annotate all the data accurately. There were instances where the algorithm was not able to find any athlete, in addition to situations where the algorithm was not able to estimate their pose and/or COM accurately. This problem was primarily present for station 2 where forest was in the background and the contrast in the black and white images was not sufficient to distinguish the athlete. Hence, visual inspections were performed on all the data generated from CV-predictions. Every image where CV had failed in estimating and annotating the COM of the athlete, was manually annotated. Manual annotation of the COM was conducted in customized QDaedalus software, QSecAnalysis5 by two raters. In order to reduce the variability in the annotations between the two raters annotating the images, the researchers were undergoing a training to limit the interrater variability prior to annotation. The annotated data was stored, allowing for it to be used in the reconstruction of the athlete's 3D position.

3.3.4 Reconstruction of the athlete’s centre of mass as 3D-position

After the COM was CV- and manually-annotated in the image files, the information was used along with the QDaedalus tracking information (angles, position, time synchronization) to calculate raw 3D positions using a forward intersection method.

The calculation of the 3D-position of the athlete in each recorded frame was calculated with a custom-made software that was established in MATLAB (MathWorks AS, Natick, MA, US). This method uses the QDaedalus total station and reference direction position recorded by the dGNSS, the GPS-time based time synchronization of the two QDaedalus total stations, the angle measurements of the QDaedalus total stations to the athlete, and the image information with the annotated COM-image coordinates. This information was then used in a *forward intersection* to calculate the 3D-position. To perform this intersection, the direction of the QDaedalus total stations (presented as angle between the baseline and the direction of the QDaedalus total station when recording the athlete) were used from both stations to get an intersection at where the centre point of the QDaedalus total stations direction pointed at. The intersection was found at where there were two annotated COM in neighbouring images from one station and an image that was time-wise within these two as the point where the distance between the intersection was minimal. Then, the pixel-to-angle ratio in both horizontal and vertical directions were calculated using the distance between QDaedalus total stations and intersection point. That ratio was then used along with the image coordinates of the COM annotation to correct that first intersection direction with the vector from QDaedalus total stations through the annotated COM-position in the images to the true 3D-position of the athlete’s COM (figure 16) (Vosselman, 2001, p.24).

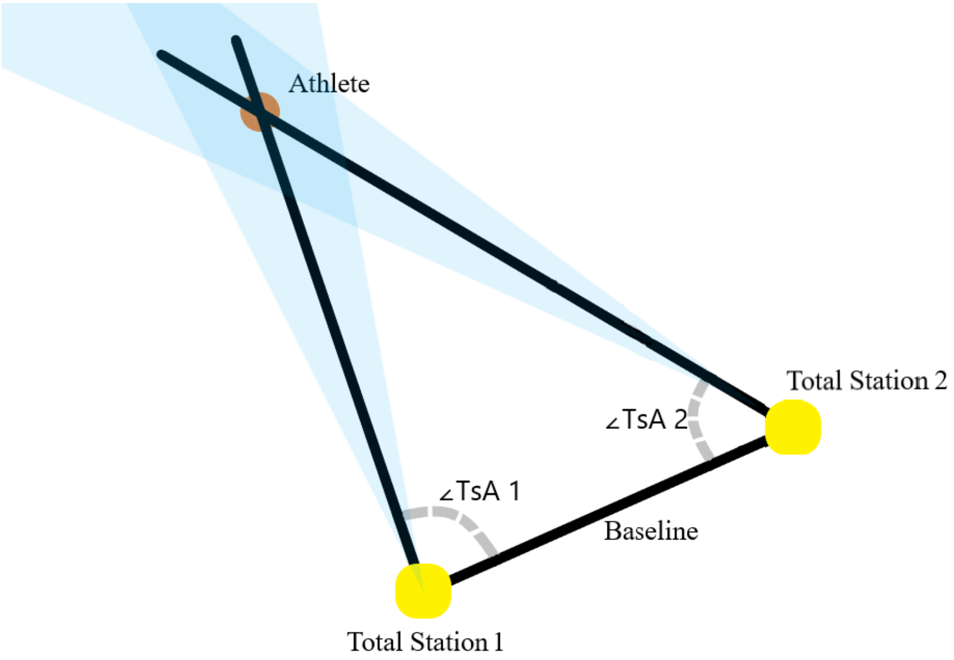

Figure 16: Visual representation of the process allowing for the calculation of the athlete's COM. The QDaedalus total stations (position 1 and 2) recording the athlete (brown circle), where the area captured by the QDaedalus total stations are shaded by light blue. By using the direction of the QDaedalus total stations (represented by the angle between the Baseline and the athlete's COM (∠TsA 1 and ∠Tsa 2)), the intersection can be found, allowing for forward intersection to be used in assessing the position of the COM.

3.3.5 Coordinate system alignment between COM trajectories and DTM

After the 3D-coordinate systems for the trajectories and the digital terrain model were established, we performed a Helmert transformation to align these two coordinate systems. To be able to perform this transformation of a coordinate system, it was required that the coordinate systems have common reference points, allowing us to find the differences between the systems and shift and rotate one into the other. We used the corner of the jumps for this purpose, as these are points in each coordinate systems that are distinct. First, the corners of all three jumps were marked in the trajectory coordinate systems using the QDaedalus software, while the mapped 3D-model of the course allowed selection of the corners. By looking at the differences between the reference points (e.g., difference between right corner of the first jump in the two coordinate systems) the translation and rotation coefficients of the Helmert transformation were calculated and the one coordinate system transformed into the other. An excerpt of the transformed course profile can be seen in figure 13.

To make it easier to perform calculations, we transformed each of these coordinate systems into a new local coordinate system. By defining a direction from the mid-point (in transversal direction) of the first jump’s kicker to the kicker of the last jump, the longitudinal axis was defined. A common point on that longitudinal axis was defined as the origin and a local coordinate system was defined with the longitudinal axis, gravity in vertical direction and the normal direction to these as the third component. The reason for this is that we now have aligned the local coordinate system in a way where any displacement in one of the directions is represented by an increase (or decrease, depending on the direction of the displacement) in the values of a single axis. Any displacement in the horizontal direction along the course would increase the values of the Y-coordinates (assuming the athlete is riding down the course),vertical displacement would be represented by a change in the z-values, and sideways movements would be represented either by a positive or negative change in the x-values, depending on whether they moved to the right or the left of the course.

3.3.6 Exclusion criteria

In order to enhance the reliability and validity of the data, criteria of exclusion were defined for take-off and landing data using the raw data points of the COM-trajectory. Due to the background problems in the airborne phase, not all runs that were measured had sufficient quality due to lack of COM-data in frames where annotation was difficult. To automatically detect cases where the number of reconstructed frames was too low the following criteria were set up. A jump was excluded if 1) there were less than one raw data point one metre ahead of the take-off point (horizontal direction), 2) there were less than one raw data point one metre after the take-off point (horizontal direction), 3) there were less than four raw data points one to five metres after the take-off (horizontal direction), 4) there were less than one raw data point ten to five metres before landing (horizontal direction), 5) less than three raw data points five metres before landing, and 6) less than one data point three metres after the landing (horizontal direction). As it is possible that there exist errors in the annotated data in the vertical direction not caught by the algorithm, the raw data points of the trajectories were inspected visually in addition to the exclusion criteria, and lead to a reduction of a total 1248 performed jumps collected to 273 jumps ready for analysis.

3.3.7 Determining the point of take-off and landing

To find the specific landing and take-off times for all runs, the images of the runs were visually inspected. The time of take-off and landing was recorded in the runs where it was possible to identify the exact time of take-off and landing. This was possible for 368 performed jumps (157 in jump 1, 103 in jump 2, and 108 in jump 3). These runs were then used to establish an automatic method to find a point of take-off and landing in all jumps. To find the point of take-off, the average position of all the known take-off positions was calculated and used as the point of take-off used in analysis in all of the performed jumps. For the point of landing, an imaginary layer was placed above the snow surface. The point of landing was defined as the point where the COM-trajectory of the athlete and the imaginary layer intersected. Heights between 0.8 and 1 metres above the snow surface were tested and compared to the timepoints of landing that were detected manually. It was found that a height of 0.9 metres above the snow surface corresponded the best with the observed values of landing positions, with a mean error of 0.37m ± 0.33.

3.4 Data smoothing

When performing manual annotations, it is difficult to avoid human errors (Rhodin et al., 2018, p. 8437). When we interpolate data without any smoothing, the trajectory will go by each of the points that we have marked. Considering that the data points can include errors, an interpolation of the trajectory could lead to some faulty data and a trajectory that looks jagged, sporadically moving more up and down than what would be natural. A smoothing spline function was laid through the raw positions. Given that especially the aerial phase is a very smooth motion, comparable to the trajectories of alpine ski racing, Skaloud & Limpach (2003, p. 4) suggested that a smoothing-factor of 0.5 – 0.75 was fit to receive satisfactory data in alpine skiing. Considering the resemblance between the sports, a cubic smoothing spline with a smoothing-factor of 0.6 ($\lambda = 0.6$) was therefore applied when interpolating, where λ set to 1 would result in a line that went through each of the annotated COM-data and λ set to 0 would produce a straight line based on all the points. The objective with this was to remove the chances of human errors influencing the trajectory and calculations, and to acquire a trajectory that is more likely to represent the real trajectory of the athlete's COM. The trajectories following the smoothing was inspected and thoroughly checked for quality to make sure that the time at take-off and landing was as close as possible as inspected time points for take-off and landing. First, the raw data points of the runs were interpolated over time with a frequency of 30 Hz. Then, in order to allow direct comparisons between the COM-trajectories, the runs were interpolated over distance with data points for every 6 cm (5000 data points total across the three jumps). An example of the COM-trajectory following the smoothing can be seen in figure 17.

3.5 Parameter calculation

Calculations of all parameters are based on the spline filtered 30Hz position – time trajectory data. Velocity and speed were calculated as position - time derivation over four points, using a central difference methodology (Gilat & Subramaniam, 2014, p. 306). These trajectories were also used to calculate the angles between COM-trajectories and the take-off and landing surface as described below.

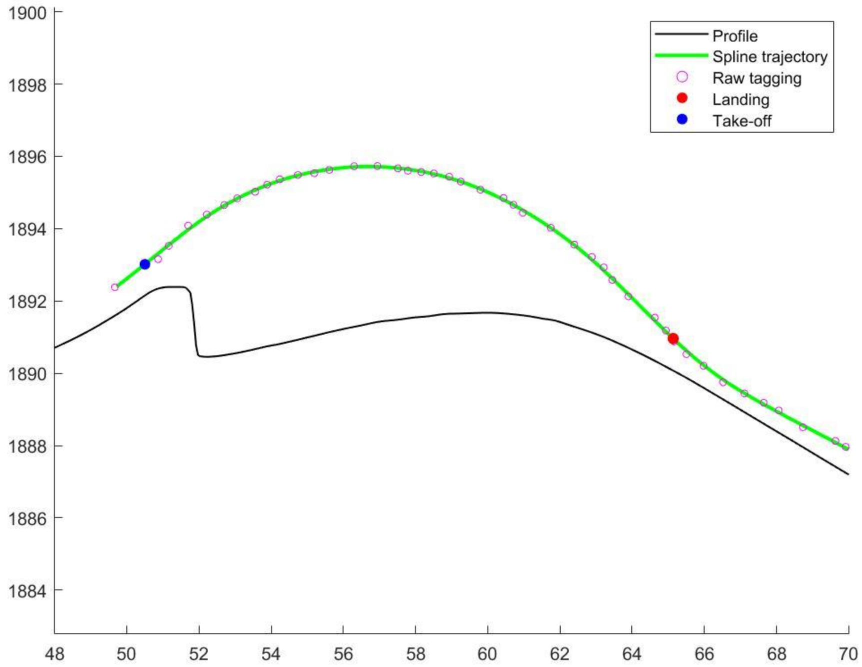

Figure 17: Trajectory of an athlete's centre of mass following the cubic spline smoothing (green line). The white dots are the raw annotated tagging points, the red dot the point of landing and blue the point of take-off. The black line represents the jump profile

To calculate how much athletes pop'ed and $V_{parallel}$ the athlete had during the point of take-off, the velocity vector was decomposed at take-off to find the velocity perpendicular and parallel to the landing. By using the angles of the snow surface and trajectory in the take-off, the take-off angle was calculated as the difference between the snow surface and trajectory angles. The angle of the terrain at take-off was calculated by projecting the velocity vector at take-off onto the snow surface profile. Subsequently the angle between the projected vector and the horizontal was calculated. For details see Gilgien et al. (2015, p. 8). The angle of the velocity vector to the horizontal was calculated accordingly and used as the global take-off direction (Gilgien et al., 2015, p. 8). The difference between these vectors was used to decompose velocity parallel to the surface and perpendicular to the surface, representing the pop expressed in m/s. A similar approach was used to define the landing angle, where the differences between the snow surface angle and the angle of the velocity vector in the landing was calculated to express the landing angle.

Hence, decomposition of the take-off velocity vector, leads to the pop as the velocity perpendicular to the take-off surface as

$$\vec{v}_{Pop} = \vec{v} \cdot \sin(angle) \qquad \text{(Equation 6)}$$

where $\vec{v}$ = the take-off velocity vector, sin(angle) = sine of the angle between the snow surface at take-off and the take-off-velocity angle, and $\vec{v}_{Pop}$ = the velocity perpendicular to the surface (pop).

To represent the amplitude of performed jumps, the flight time and vertical jump height was calculated. The flight time was found by calculating the time-difference in the recorded GPS-time data between the point of landing and point-off take-off. The vertical jump height was calculated by finding the difference between the position (z-axis) of the athlete at the highest point of the COM-trajectory and the point of take-off in vertical direction.

The horizontal jump distance was calculated as the difference between the COM-position at the point of landing and the point of take-off in the horizontal/transversal direction (Y-value).

To represent the complexity of the tricks performed by an athlete, the rotational velocity (angular velocity) was used. Another Masters student at the Norwegian School of Sports Sciences (Mai-Sissel Linløkken: A biomechanical analysis of how rider behavior and equivalent fall height affect landing stability in World Cup Slopestyle for ski and snowboard) inspected and noted how many rotations the athlete performed while airborne and whether the rotations were around one (monoaxial) or several axes (poly-axial) in each jump. The student also qualitatively assessed the time of take-off and landing, which was used specifically for the calculation of the average angular velocity while airborne. By using equation 7, where $\Delta\theta$ is the angular displacement from take-off (θ_0) to the landing (θ_1) , and Δt being the difference in time between the landing (t_1) and take-off (t_0) of the qualitative assessed flight time, we were able to calculate the average angular velocity (ω_{avg}) during flight time.

$$\omega_{avg} = \frac{\Delta\theta}{\Delta t} = \frac{\theta_1 - \theta_0}{t_1 - t_0} \qquad \text{(Equation 7)}$$

To calculate the EFH, we used the established equation using the landing velocity vector and the projection of the landing velocity vector to the snow surface to calculate the angles of the these to the horizontal following the same procedure as for the take-off (pop and $V_{parallel}$). From these, the EFH was calculated according to Equation 3.

3.6 Analysis

IBM SPSS (IBM Corp., Armonk, NY, US) was used to perform tests of normality on the data. Considering the number of observed values, the Kolmogorov-Smirnov and/or Shapiro-Wilk test was used (dependent on sample size) to assess the normality of the data, where a significant result could signify that the data was not normally distributed. The histogram and QQ-plots made by IMB SPSS were additionally inspected to give further and final insight into whether the data was normally distributed or not. IBM SPSS was also used to perform all analysis on the data, including bivariate correlations (Spearman’s rho), linear regression, one-way ANOVA, independent samples t-test, descriptive, etc. The overview of which test that was used on which data groups are presented in table 2, 3 and 4. Normally distributed data is represented as mean and standard deviation (±), while not normally distributed data is represented by median and interquartile range (IQR) as the spread.

Table 2: The multiple regression models proposed to assess whether the independent variables could predict the dependent variable within the groups.

Dependent variable	**Independent variables**	**Groups**
Horizontal jump distance	$V_{parallel}$, the pop	All athletes combined, within skiers and within snowboarders
Flight Time	$V_{parallel}$, the pop	All athletes combined, within skiers and within snowboarders
Number of rotations	Flight time, average angular velocity	All athletes combined, within skiers and within snowboarders
EFH	$V_{parallel}$, the pop	All athletes combined, within skiers and within snowboarders
EFH	$V_{parallel}$, the pop, landing angle	All athletes combined, within skiers and within snowboarders

Table 3: The test performed to compare and investigate the differences in the observed mean (or median) values of variables between Samples.

Variable	Samples	Test
Pop	Skiers, snowboarders	Independent samples T-test
	Male skiers, female skiers	Independent samples T-test
	Male snowboarders, female snowboarders	Independent samples T-test
	Jump1, jump 2, jump 3	One way ANOVA w/ Bonferroni correction
$V_{parallel}$	Skiers, snowboarders	Mann Whitney U-test
	Male skiers, female skiers	Mann Whitney U-test
	Male snowboarders, male snowboarders	Mann Whitney U-test
	Jump 1, jump 2, jump 3	Kruskal-wallis w/ Dunn-Bonferroni correction
Horizontal jump Distance	Skiers, snowboarders	Independent samples T-test
	Male skiers, female skiers	Mann Whitney U-test
	Male snowboarders, female snowboarders	Mann Whitney U-test
	Jump 1, jump 2, jump 3	One way ANOVA w/ Bonferroni correction
Flight time	Skiers, snowboarders	Independent samples T-test
	Male skiers, female skiers	Independent samples T-test
	Male snowboarders, female snowboarders	Independent samples T-test
	Jump 1, Jump 2, jump 3	One way ANOVA w/ Bonferroni correction

Table 3 (continued)

Variable	**Samples**	**Test**
Vertical jump height	Skiers, snowboarders	Mann Whitney U-test
	Male skiers, female skiers	Mann Whitney U-test
	Male snowboarders, female snowboarders	Mann Whitney U-test
Landing angle	Skiers, snowboarders	Independent samples T-test
	Male skiers, female skiers	Independent samples T-test
	Male snowboarders, female snowboarders	Independent samples T-test
EFH	Skiers, snowboarders	Mann Whitney U-test
	Male skiers, female skiers	Mann Whitney U-test
	Male snowboarders, female snowboarders	Mann Whitney U-test

Table 4: The test performed to investigate the correlation/relationship between the variables within groups.

Variables	**Groups**	**Test**
$V_{parallel}$, pop	All athletes combined, skiers, snowboarders, female skiers, male skiers, female snowboarders, male snowboarders	Spearman’s rho-test
$V_{parallel}$, average angular velocity	All athletes combined, skiers, snowboarders	Spearman’s rho-test
Pop, average angular velocity	All athletes combined, skiers, snowboarders	Spearman’s rho-test

3.7 Ethical Considerations

To ensure that the project follows the ethical guidelines for research, applications were sent to, and approved by, the Norwegian School of Sports Sciences Ethical Committee and the Norwegian Centre for Research Data. The application ids are:

- Norwegian School of Sports Sciences Ethical Committee: Application 11-130617 – Utvikling av en valid verktøy for simulasjon av hopp konstruksjon i slopestyle og big air.
- Norwegian Centre for Research Data: USD – Utvikling av en valid verktøy for simulasjon av hopp konstruksjon i slopestyle og big air.

4. Results

In total, 416 runs were recorded. All runs consist of three jumps, and the total amount of performed jumps recorded was 1248. After analysing the data and applying the exclusion criteria, 273 performed jumps remained available for analysis of all athletes (skiers and snowboarders). The distribution of included jumps that athletes performed can be seen in table 5. For 12 of the performed jumps (6 skiers and 6 snowboarders) it was not possible to discern the sex of the recorded athlete. These 12 performed jumps were used in analysis when investigating all athletes (skiers and snowboarders), skiers and snowboarders, but excluded when analysing the athlete groups (female and male athletes) within skiers and snowboarders.

Table 5: Distribution (number of) of recorded jumps within all athlete groups.

Athlete groups	**Ski**	**Snowboard**	**Total**
Female athletes	73	22	95
Male athletes	76	90	166
Unknown sex	6	6	12
All athletes	155	118	273

The course profile that was generated using data from the digital terrain model and can be seen in figure 18 with information regarding the different jumps. Jump 1 and 2 can be defined as roll-over jumps, while jump 3 is considered a step-up jump. Wind measurements were below 3 m/s and rather constant in the competition days (graphs with measurements can be seen in appendix 1).

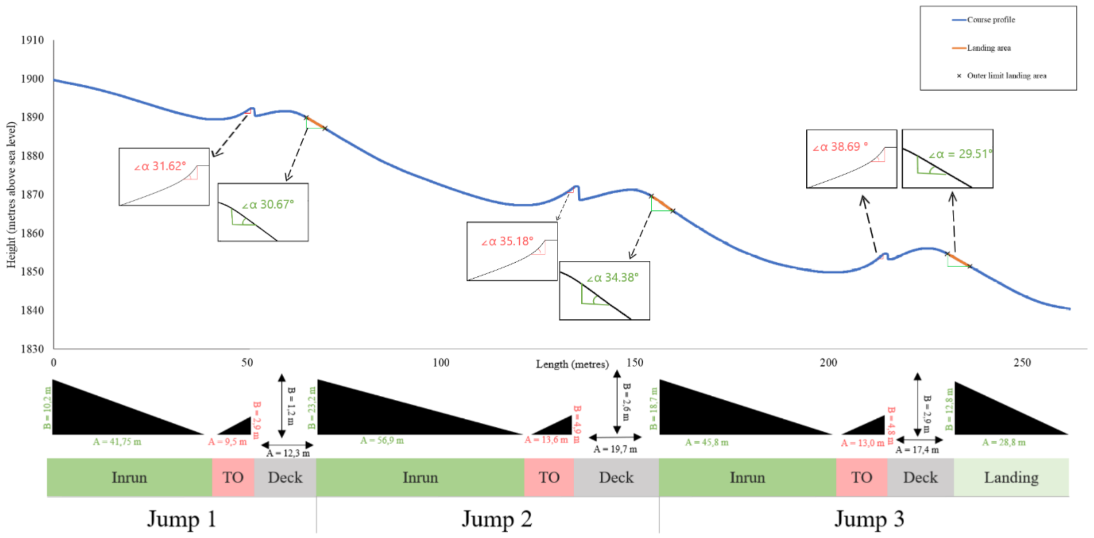

Figure 18: Course profile with definitions of inrun, take-off (TO), deck and landing for each of the jumps. Angles of the surface at point of take-off (red) and landing (green) are specified.

For the 273 included jumps that were performed, the observed values of pop ranged from -2.32 m/s to +2.20 m/s, with a mean of +0.09 ± 0.73 m/s. The ranges of pop in jump 1, jump 2 and jump 3 were -1.28 to +2.20 m/s, -1.77 to +1.16 m/s, and -2.32 to +1.26 m/s respectively, with mean values of pop for the three jumps separately being presented in table 6 (scatter plot with range and individual data points can be seen in appendix 2). When analysing the differences between the jumps for all athletes combined, the values of pop was observed to be significantly higher in jump 1 than in the other two jumps ($p<0.001$) by a mean of +0.61 m/s (CI95%: 0.39 – 0.84) more than in jump 2 and +0.87 m/s (CI95%: 0.64 – 1.10) more than in jump 3. Pop values were also different between jump 2 and 3 ($p<0.05$), where the athletes were observed to pop +0.26 m/s (CI95%: 0.01 – 0.513) more in jump 2 than jump 3. The distance, flight time and $V_{parallel}$ within the three jumps can be seen in table 6. The one-way ANOVA-tests with Bonferroni corrections showed that there was a significant difference in the horizontal jump distance between all three jumps ($p<0.001$), where athletes on average jumped 5.35 metres and 2.24 metres longer in jump 2 and jump 3 respectively than in jump 1, and 3.1 metres longer in jump 2 than jump 3. Analysis also showed that the flight time of the athletes was longer in jump 2 than jump 1 and jump 3 by an average of 0.28 s and 0.19s respectively ($p<0.001$). The flight time over jump 3 was also considered to be longer than in jump 1 by 0.89s ($p<0.005$). When analysing the $V_{parallel}$ for the three jumps, the Kruskal Wallis-test showed that jump 1 had a lower $V_{parallel}$ than jump 2 and 3 ($p<0.001$), while no difference was found between jump 2 and 3.

Table 6: The distribution of recorded jumps, the angle of the take-off surface and the observed mean values of the horizontal jump distance, flight time, $V_{parallel}$, and the pop in each of the three jumps.

Variable	**Jump 1**	**Jump 2**	**Jump 3**
n	**115**	**83**	**75**
Angle of take-off surface (º)	31.6	35.2	38.7
Horizontal jump distance (m)	16.7 (± 2.3) **	22.0 (± 2.2) **	18.9 (± 2.7) **
Flight time (s)	1.86 (± 0.18) *	2.14 (± 0.17) **	1.94 (± 0.23) *
$V_{Parallel}$	11.27 (IQR: 0.97) **	14.29 (IQR: 0.85)	14.34 (IQR: 1.06)
Pop	+0.46 (± 0.63) **	-0.16 (± 0.61) *	-0.41 (± 0.70) *

* Significantly different from other jumps (<0.005).
** Significantly different from other jumps (<0.001).

When comparing the three jumps with the variety of jumps that are built in parks and for competition, the three jumps that were assessed in this study can be considered to be quite similar. Since, there are a small number of performed jumps in some of the athlete groups (table 5) for the investigation of the jumps separately. Hence, analysis within and between athlete groups were performed on all three jumps combined.

To investigate the relationship between the $V_{parallel}$ and the values of pop and our hypothesis H6: “Higher $V_{parallel}$ at take-off is related to lower values of pop for both skiers and snowboarders in typical jumps in slopestyle World Cup”, a Spearman’s rho-test was performed on the $V_{parallel}$ and the pop for all athletes (skiers and snowboarders combined) and within the groups of skiers and snowboarders (figure 19). The correlation between the $V_{parallel}$ and the pop for the all athletes (skiers and snowboarders) was observed to be -0.463 (CI95%: -0.554 – -0.361) and the relationship was observed to be significant (p<0.001). Within the groups of skiers and snowboarders, the correlation was observed to be significant (p<0.001), where the correlation was -0.546 (CI95%: -0.651 – -0.421) and -0.274 (CI95%: -0.437 – -0.092) respectively.

Additionally, the relationship between the $V_{parallel}$ and the pop was investigated within female and male athletes within the population of skiers (figure 20) and snowboarders (figure 21). The correlation was found using a nonparametric Spearman rho-test, and a significant relationship were found within female skiers, male skier and male snowboarders ($p<0.001$), while this relationship was not significant for female snowboarders. The correlation between the $V_{parallel}$ and the pop were -0.523 (CI95%: -0.676 – -0.327) within female skiers, -0.599 (CI95%: 0.729 – -0.426) within male skiers, and -0.333 (CI95%: -0.510 – -0.158) within male snowboarders.

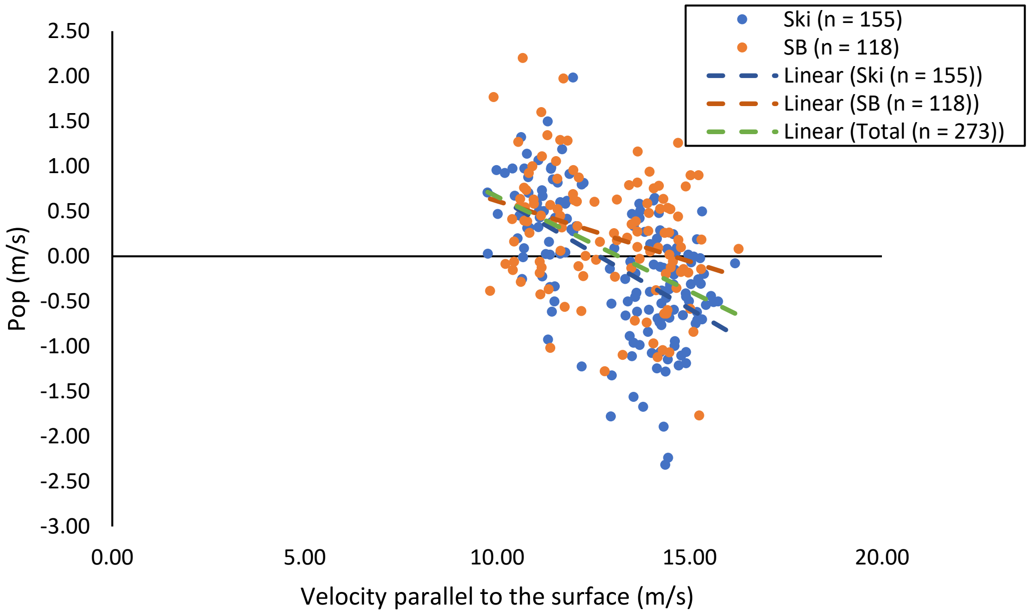

Figure 19: The relationship between the velocity parallel to the surface and the pop for all athletes (skiers and snowboarders) in all jumps combined. The observed data from skiers are represented by a blue dot, and the snowboarders by an orange dot. The green striped line represents the correlation between the two variables for the all athletes (skiers and snowboarders).

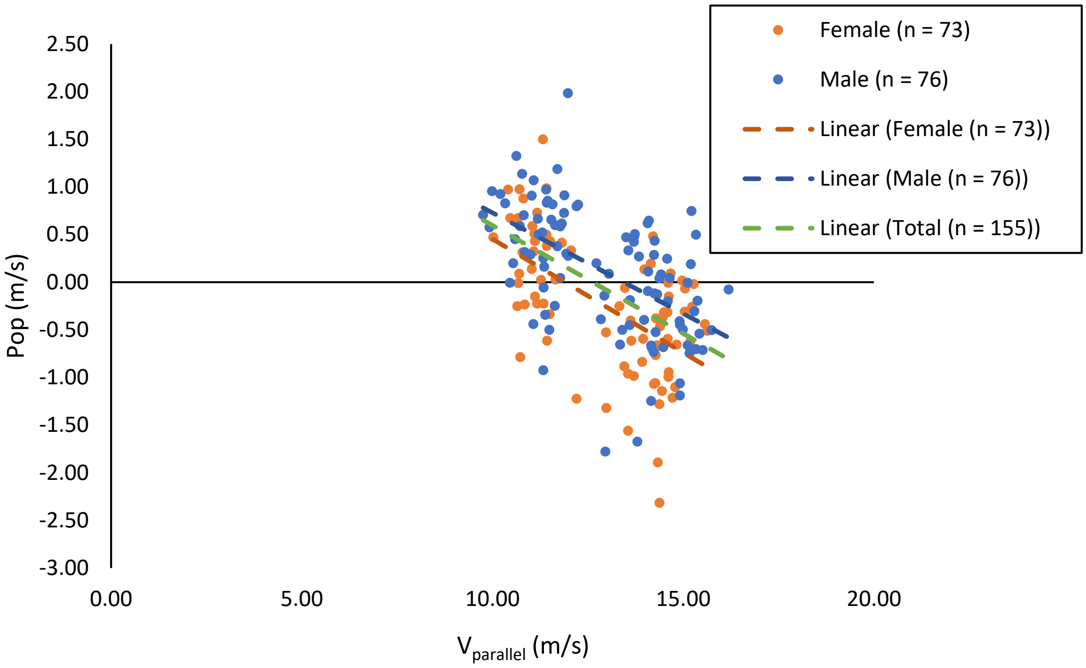

Figure 20: The relationship between the $V_{parallel}$ and the pop for skiers in all jumps combined. The observed data of female skiers are presented by an orange dot and male skiers by a blue dot. The green striped line represents the correlation between the two variables for skiers, the dark orange the female skiers and the dark blue the male skiers.

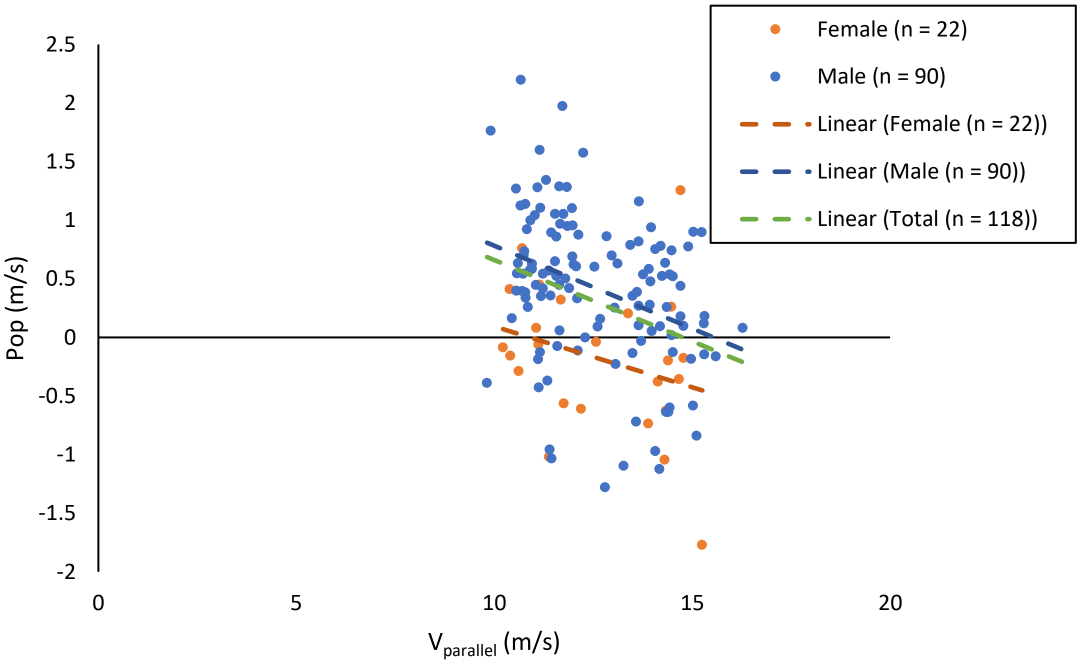

Figure 21: The relationship between the $V_{parallel}$ and the pop for snowboarders in all jumps combined. The observed data of female snowboarders are presented by an orange dot and male skiers by a blue dot. The green striped line represents the correlation between the two variables for snowboarders, the dark orange the female snowboarders and the dark blue the male snowboarders.

Table 7 shows values and comparisons between the population of skiers and snowboarders for pop and parameters that can be related to pop either as pre-condition or consequence. In order to compare the parameters between skiers and snowboarders, an independent samples T-test was applied. Significant differences were found in the pop performed between skiers and snowboarders, where snowboarders on average were observed to have 0.36 m/s (CI95%: 0.54 – 0.19) higher values of pop than skiers. Parameters that could be related to pop either as pre-condition or consequence were compared between skiers and snowboarders using tests specified in table 3. The analysis showed that there were no differences in the average values of $V_{parallel}$, the horizontal distance of the performed jump, flight time, the vertical jump height, landing angle or EFH between skiers and snowboarders.

Table 7: The average observed values for pop, horizontal jump distance, flight time and landing angle, and the median of the $V_{parallel}$, vertical jump height, and EFH within the group of skiers and snowboarders.

Variable	**Skiers**	**Snowboarders**	
n	**155**	**118**	
Pop (m/s)	-0.13 (± 0.75)	+0.23 (± 0.75)	**
$V_{Parallel}$ (m/s)	13.70 (IQR: 3.03)	13.05 (IQR: 3.05)	
Horizontal jump distance (m)	19.1 (± 3.3)	18.7 (± 3.3)	
Flight time (s)	1.96 (± 0.22)	1.97 (± 0.24)	
Vertical jump height (m)	3.72 (IQR: 1.45)	3.43 (IQR: 1.68)	
Landing angle (º)	12.67 (± 3.10)	13.27 (± 3.41)	
EHF (m)	0.46 (IQR: 0.29)	0.48 (IQR: 0.29)	

* Significant difference between skiers and snowboarders ($p<0.05$)
** Significant difference between skiers and snowboarders ($p<0.001$)

To investigate whether the horizontal jump distance could be explained by the $V_{parallel}$ and the pop, a multiple regression analysis was performed with a model using $V_{parallel}$ and pop as independent factors that were to predict the horizontal jump distance. The output of the model for all athletes (skiers and snowboarders) can be seen in table 8, and analysis showed that the model was significantly able to predict the horizontal jump distance ($p<0.001$). The model explained 58.4% ($r^2 = 0.584$) of the variation in the distance and every increment of either factor would increase the predicted output (by the beta-value listed in table 8). To investigate this for skiers and snowboarders specifically, the model was applied within the population of skiers and snowboarders, as can be seen in table 9 and 10. The models were observed to be significant predictors of the horizontal jump distance ($p<0.001$), where the model in skiers could explain 65.8% ($r^2 = 0.658$) of the variance found in the horizontal jump distance and 49% ($r^2 = 0.490$) of the variation observed within snowboarders. Both the coefficient of $V_{parallel}$ ($p<0.001$) and the pop ($p<0.05$) differed from 0 in positive direction within skiers, meaning that an increase in the variable would increase the predicted output. For snowboarders, the coefficient of the $V_{parallel}$ was different from 0 in the positive direction ($p<0.001$), while it's uncertain whether an increase in the pop would lead to an increase in the predicted horizontal jump distance, as its confidence intervals (CI) was not different from 0 for snowboarders.

Table 8: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the horizontal jump distance within all athletes (skiers and snowboarders), and the change in the predicted horizontal jump distance with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI95% lower bounds**	**CI95% higher bounds**	
Constant	-2.177	-4.452	0.099	
$V_{parallel}$ (m/s)	1.620	1.447	1.794	**
Pop (m/s)	0.584	0.199	0.969	*

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

Table 9: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the horizontal jump distance within skiers, and the change in the predicted horizontal jump distance with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI95% lower bounds**	**CI95% higher bounds**	
Constant	-3.935	-6.851	-1.020	*
$V_{parallel}$ (m/s)	1.759	1.537	1.982	**
Pop (m/s)	0.698	0.204	1.193	*

* 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)

Table 10: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the horizontal jump distance within snowboarders, and the change in the predicted horizontal jump distance with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI95% lower bounds**	**CI95% higher bounds**	
Constant	-0.220	-3.861	3.422	
$V_{parallel}$ (m/s)	1.461	1.183	1.740	**
Pop (m/s)	0.610	-0.046	1.266	

* 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)

In table 11, the mean and median values and comparisons for pop and parameters that can be related to pop either as pre-condition or consequence between the female and male athletes within the two populations are presented. The independent samples T-test was used to assess the differences in the variables where there were observed a normal distribution of the data and Mann-Whitney U test for the variables where this assumption couldn’t be hold based on the distribution of the data. The analysis found that the male athletes within both populations (ski and snowboard) on average were observed to pop more than their female counterparts (skiers: $p<0.05$, snowboarders:

p<0.001). The male skiers pop on average 0.36 m/s (CI95%: 0.13 – 0.59) more than female skiers, and male snowboarders pop 0.54 m/s (CI95%: 0.23 – 0.85) more than female snowboarders. Further analysis into the differences between the female and male athletes within the two populations showed that in both skiers and snowboarders, the male skiers and male snowboarders had a longer flight time and higher vertical jump height compared to their female counterparts ($p<0.05$). No differences were found in the values of $V_{parallel}$, horizontal jump distance, landing angle or EFH between female and male athletes within either of the two populations (skiers and snowboarders).

Table 11: The average observed values for pop, flight time and landing angle, and the median of the $V_{parallel}$, horizontal jump distance (Jump distance), the vertical jump height (Jump height), and EFH in female and male athletes within skiers and snowboarders.

Variable	**Skiers**			**Snowboarders**		
	Female	**Male**		**Female**	**Male**	
n	**73**	**76**		**22**	**90**	
Pop (m/s)	-0.29 (± 0.71)	+0.07 (± 0.71)	*	-0.17 (± 0.66)	+0.37 (± 0.66)	**
$V_{Parallel}$	13.93 (IQR: 3.12)	13.60 (IQR: 2.96)		12.38 (IQR: 3.40)	13.05 (IQR: 2.88)	
Jump distance (m)	19.25 (IQR: 5.45)	19.48 (IQR: 4.59)		16.70 (IQR: 6.10)	18.64 (IQR: 4.31)	
Flight time (s)	1.93 (± 0.21)	2.00 (± 0.21)	*	1.84 (± 0.25)	2.01 (± 0.22)	*
Jump height (m)	3.65 (IQR: 1.43)	3.83 (IQR: 1.51)	*	3.04 (IQR: 1.59)	3.36 (IQR: 1.67)	*
Landing angle (º)	12.34 (± 2.71)	12.96 (± 3.51)		12.93 (± 3.11)	13.21 (± 3.45)	
EFH (m)	0.44 (IQR: 0.25)	0.49 (IQR: 0.37)		0.42 (IQR: 0.21)	0.51 (IQR: 0.31)	

* Significant difference between female and male athletes within discipline ($p<0.05$)
** Significant difference between female and male athletes within discipline ($p<0.001$)

4.1 Pop and its relation to performance variables

To investigate the relation between the $V_{parallel}$, the pop and the flight time (figure 1) and to assess the hypothesis H1: "Higher values of positive pop is related to increased flight time for both skiers and snowboarders in typical jumps in slopestyle World Cup" and H2: "Higher $V_{parallel}$ at take-off is related to increased flight time for both skiers and snowboarders in typical jumps in slopestyle World Cup.", a multiple regression analysis was used with flight time as the dependent factor, and $V_{parallel}$ and the pop as predicting independent factors for all athletes (skiers and snowboarders) combined (table 12). The one-way ANOVA-test complimentary to the multiple regression analysis, showed that the model was significant ($p<0.001$) in predicting the flight time, with the $V_{parallel}$ and pop being able to explain 50% ($r^2 = 0.501$) of the variation observed in flight time. The coefficients of the $V_{parallel}$ and the pop was significantly different from 0 ($p<0.001$), where every increment in either pop or $V_{parallel}$ would predict an increase in the predicted flight time (by the size of the beta-value in table 12). To investigate the flight time within equipment groups, the model was applied for skiers and snowboarders separately (table 13 and 14 respectively). The one-way ANOVA-test showed that it is possible to predict the flight time based on the $V_{parallel}$ and the pop for skiers and snowboarders ($p<0.001$), where the $V_{parallel}$ and the pop was able to explain 55.5% ($r^2 = 0.555$) of the variation observed in flight time of skiers and 45% ($r^2 = 0.45$) of the variation of snowboarders. Similar to the model used on all athletes (skiers and snowboarders), the coefficient of $V_{parallel}$ and the pop was found to be different from 0 in the positive direction ($p<0.001$), and an increase in either pop or $V_{parallel}$ would result in an increase in the predicted flight time within skiers and snowboarders (by the size of beta-value in table 13 and 14).

Table 12: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the flight time within all athletes (skiers and snowboarders), and the change in the predicted flight time with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	0.554	0.383	0.724	**
$V_{parallel}$ (m/s)	0.108	0.095	0.121	**
Pop (m/s)	0.123	0.094	0.152	**

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

Table 13: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the flight time within skiers, and the change in the predicted flight time with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	0.462	0.245	0.679	**
$V_{parallel}$ (m/s)	0.115	0.098	0.132	**
Pop (m/s)	0.120	0.083	0.157	**

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

Table 14: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the flight time within snowboarders, and the change in the predicted flight time with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	0.666	0.392	0.941	**
$V_{parallel}$ (m/s)	0.099	0.078	0.120	**
Pop (m/s)	0.133	0.083	0.182	**

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

To investigate the relation between the number of rotations, average angular velocity and flight time illustrated and proposed in figure 1 and H3: “Longer flight time is related to a larger number of rotations during flight for both skiers and snowboarders in typical jumps in slopestyle World Cup.”, and H4: “Higher average angular velocity is related to a larger number of rotations during flight for both skiers and snowboarders in typical jumps in slopestyle World Cup.”, a multiple regression model using the average angular velocity and flight time to predict the number of rotations performed for all athletes (skiers and snowboarders) combined. The output of the proposed model can be seen in table 15. The flight time and average angular velocity were able to significantly explain 98.4% ($r^2 = 0.984$) of the variation in the number of rotations ($p<0.001$). The coefficients of flight time and average angular velocity were both statistically different from 0 in positive direction ($p<0.001$). To investigate whether the model could be used to describe the relationship within the two populations, the multiple regression analysis was performed within the groups of skier and snowboarders separately (table 16 and 17 respectively). The ANOVA-test showed that it was possible to use the model to predict the number of rotations based on the flight time and average angular velocity within both populations ($p<0.001$), where the flight time and average angular velocity were able to explain 98.5% ($r^2 = 0.985$) of the variation in observed number of rotations in skiers, and 98.6% ($r^2 =0.986$) of the variation observed in snowboarders. The coefficient of both average angular velocity and flight time was found to be significantly different from 0 in a positive direction in both populations ($p<0.001$), where an increment in either flight time or average angular velocity would predict an increase in the number of rotations performed (by the size of the beta-value found in table 16 for skiers and table 17 for snowboarders).

Table 15: The proposed multiple regression model used to assess whether the flight time and the average angular velocity was able to predict the number of rotations within all athletes (skiers and snowboarders), and the change in the predicted number of rotations with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	-1.917	-2.036	-1.798	**
Flight time (s)	0.975	0.915	1.035	**
Average angular velocity (°/s)	0.005	0.005	0.006	**

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

Table 16: The proposed multiple regression model used to assess whether the flight time and the average angular velocity was able to predict the number of rotations within skiers, and the change in the predicted number of rotations with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	-2.151	-2.306	-1.996	**
Flight time (s)	1.069	0.993	1.145	**
Average angular velocity (°/s)	0.006	0.005	0.006	**

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

Table 17: The proposed multiple regression model used to assess whether the flight time and the average angular velocity was able to predict the number of rotations within snowboarders, and the change in the predicted number of rotations with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	-1.679	-1.782	-1.575	**
Flight time (s)	0.871	0.819	0.923	**
Average angular velocity (°/s)	0.005	0.005	0.006	**

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

To investigate H5: ": Higher $V_{parallel}$ at take-off is related to lower average angular velocity during flight for both skiers and snowboarders in typical jumps in slopestyle World Cup". To investigate the relationship between the $V_{parallel}$ and the average angular velocity, a Spearman rho-test was performed on data on all jumps combined from all athletes (skiers and snowboarders) and the data within the two populations separately. The individual data points used and belonging trendline can be seen in figure 22. The Spearman's rho-tests were unable to find a significant correlation between the $V_{parallel}$ and the average angular velocity within all athletes (skiers and snowboarders), within the population of skiers and within the population of snowboarders. The observed rho-values were -0.059 for the population, -0.016 for skiers, and -0.104 for snowboarders.

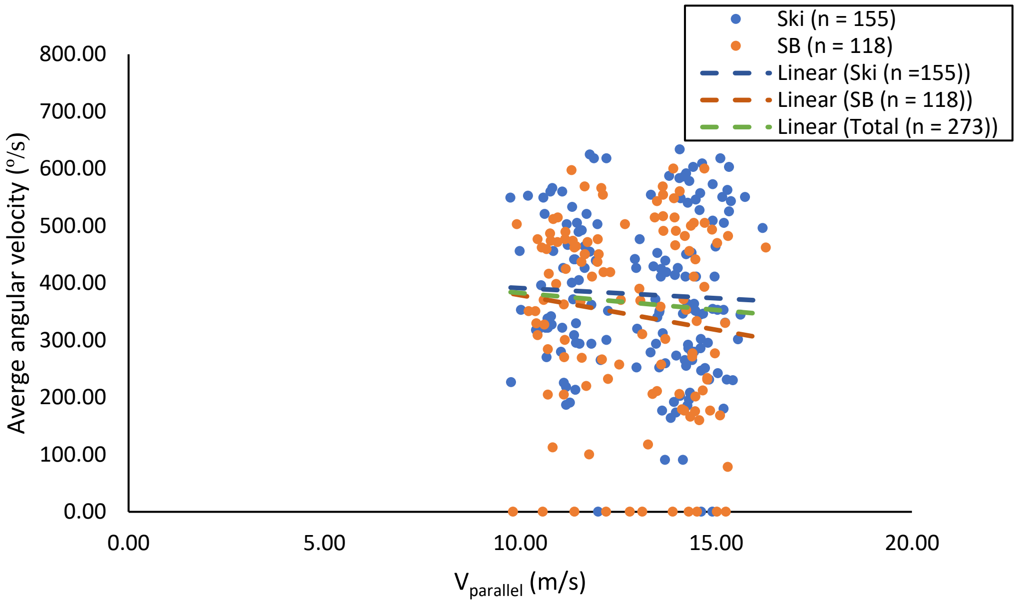

Figure 22: The individual data points (dots) and the trendline (linear striped line) of the $V_{parallel}$ *and the average angular velocity in all jumps combined. The data represents all athletes (skiers and snowboarders (total)), with skiers presented by blue dots and snowboarders with orange dots, and the trendline of the data points within all athletes (green striped line), skiers (dark blue striped line), and snowboarders (dark orange line).*

To investigate H7: "Higher values of pop is related to lower average angular velocity during flight time for both skiers and snowboarders in typical jumps in slopestyle World Cup." and the relationship between the average angular velocity and the pop, a Spearman's rho-test was used on the data from all athletes (skiers and snowboarders) and all jumps combined. Individual data points and the trendline for the relation can be seen in figure 23. A significant positive correlation was found between the two factors within all athletes (skiers and snowboarders) ($p<0.001$), with a strength (r-value) of 0.330 (CI95%: 0.216 – 0.435). The Spearman's rho-test was further tested within the two populations (skiers and snowboarders separately), and their data points and trendline are also visualized in figure 23. A significant correlation was found in both populations in the positive direction ($p<0.001$), where the strength of the correlation was found to be 0.201 (CI95%: 0.040 – 0.351) within the skiers. Within the population of snowboarders, the strength of the correlation was observed to be 0.525 (CI95%: 0.376 – 0.648).

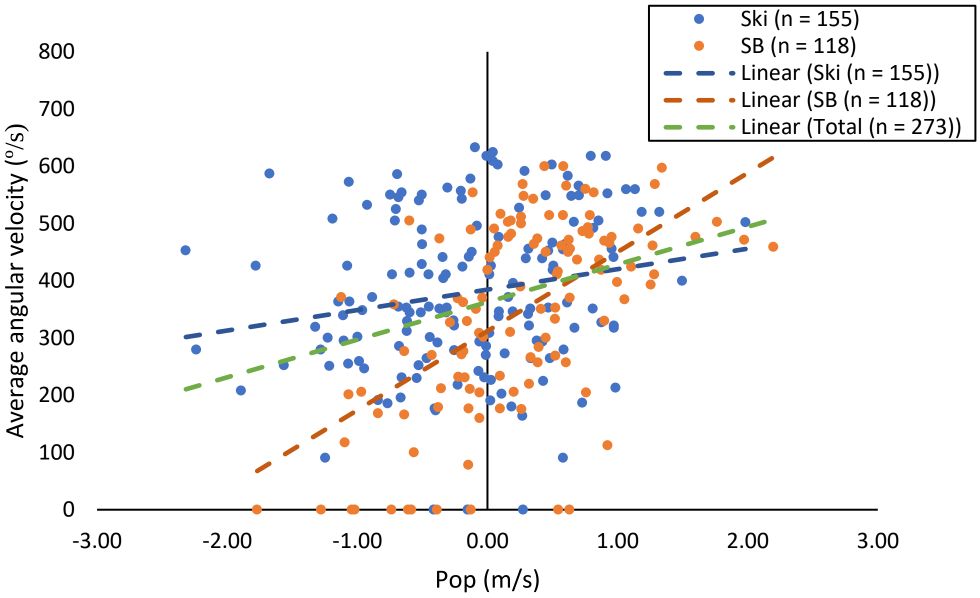

Figure 23: The individual data points (dots) and the trendline (linear striped line) of the pop and the average angular velocity in all jumps combined. The data represents all athletes (skiers and snowboarders (total)), with skiers presented by blue dots and snowboarders by orange dots, and the trendline of the data points within all athletes (green striped line), skiers (dark blue striped line), and snowboarders (dark orange line).

4.2 Pop and its impact on equivalent fall height

For all athletes (skiers and snowboarders) in all jumps combined, the EFH was observed to have a median of 0.47m (IQR: 0.29), where the observed values ranged from 0.04m to 1.37m. The median value of the population of skiers and snowboarders can be seen in table 7, while the median and comparisons of the value of the female and male athletes within the population of skiers and snowboarders separately can be seen in table 11. In order to investigate the relationship proposed in figure 3, and the hypothesis related to the figure; H8: “Higher values of positive pop is related to increased mean EFH for both skiers and snowboarders in typical jumps in slopestyle World Cup”, and H9: “Higher values of $V_{parallel}$ at take-off is related to increased EFH for both skiers and snowboarders in typical jumps in slopestyle World Cup”, a multiple regression model was proposed. The model used the pop and the $V_{parallel}$ as the independent factors, and the analysis assessed whether these could predict the EFH in the landing for all athletes (skiers and snowboarders). The proposed model and its output can be seen in table 18. Following the complimentary ANOVA-test, it was observed that the model was able to significantly predict the observed EFH ($p<0.001$), where the $V_{parallel}$ and the pop was able to explain 6.6% ($r^2 = 0.066$) of the variation observed in EFH. Both the coefficient of the $V_{parallel}$ and the pop was found to be significant different from 0 ($p<0.001$), where an increase of an increment in either would increase the predicted output (by the size of the beta-value found in table 18). The same model was proposed to be used within the population of skiers and snowboarders separately to assess whether the $V_{parallel}$ and the pop could be used to predict the observed EFH within populations. The proposed model and coefficients can be seen in table 19 for skiers and 20 for snowboarders. The ANOVA-test found that the model was able to significantly predict the EFH in both populations ($p<0.05$). Within skiers, the model was able to explain 7.1% ($r^2 = 0.071$) of the variation observed in the EFH, while within snowboarders, it was able to explain 6.4% ($r^2 = 0.064$) of the variation observed in EFH. Within skiers, the coefficients of both $V_{parallel}$ was significantly different from 0 ($p<0.05$), where an increase in either would increase the predicted output of the model. Within snowboarders, the coefficient for the $V_{parallel}$ was found to be significantly different from 0 ($p<0.05$), where an increase would increase the predicted output. The coefficient for the pop was not found to be significantly different from 0, meaning it's unclear whether an increase in the pop would increase or decrease the predicted output of EFH.

Table 18: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the EFH within all athletes (skiers and snowboarders), and the change in the predicted EFH with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	0.054	-0.191	0.300	
$V_{parallel}$ (m/s)	0.034	0.015	0.052	**
Pop (m/s)	0.083	0.041	0.124	**

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)
** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

Table 19: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the EFH within the skiers, and the change in the predicted EFH with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	0.052	-0.292	0.397	
$V_{parallel}$ (m/s)	0.034	0.008	0.060	*
Pop (m/s)	0.097	0.039	0.156	**

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

Table 20: The proposed multiple regression model used to assess whether the $V_{parallel}$ and the pop was able to predict the EFH within the snowboarders, and the change in the predicted EFH with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bounds**	**CI Higher bound**	
Constant	0.037	-0.323	0.397	
$V_{parallel}$ (m/s)	0.035	0.008	0.063	*
Pop (m/s)	0.064	-0.001	0.129	

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

To further investigate the relationship between the $V_{parallel}$, the pop and the EFH, an additional multiple regression model was applied where the landing angle was added as an additional independent factor. The model and the coefficients of the independent variables used on all athletes (skiers and snowboarders combined) can be seen in table 21. The model was able to significantly predict the output parameter EFH ($p<0.001$), with the model being able to explain 82.3% ($r^2 = 0.823$) of the variation observed in the EFH. The coefficients of the $V_{parallel}$ ($p<0.001$), the pop ($p<0.05$) and the landing angle ($p<0.001$) was different from 0 in the positive direction, where an isolated increase in either $V_{parallel}$, the pop or the landing angle would increase the predicted output (by the size of the beta-value found in table 21). The same model was used to assess whether it could be used to predict the EFH observed in the population of skiers and snowboarders, as can be seen in table 22 and 23 respectively. The model was found to significantly be able to predict the EFH in both populations ($p<0.001$), where the $V_{parallel}$, the pop and the landing angle was able to explain 85.9% ($r^2 = 0.859$) of the variation observed in the EFH within skiers. Within snowboarders, the model was able to explain 79.6% ($r^2 = 0.796$) in the observed EFH values. For skiers, the coefficients of $V_{parallel}$ and the landing angle ($p<0.001$), and the pop ($p<0.05$) was significantly different from 0, where an increase in either would increase the predicted output (by the size of the beta-value found in table 22). Within snowboarders, the coefficient of the $V_{parallel}$ and the landing angle was found to significantly differ from 0 ($p<0.001$), where an increase in either the $V_{parallel}$ or the landing angle (assuming the other independent factors stay constant) increases the predicted output of EFH. The coefficient of pop was not found significant different from 0, and it is uncertain whether an increase in the pop would increase or decrease the predicted output of EFH.

Table 21: The proposed multiple regression model used to assess whether the $V_{parallel}$, the pop and landing angle was able to predict the EFH within all athletes (skiers and snowboarders), and the change in the predicted EFH with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bound**	**CI higher bound**	
Constant	-0.890	-1.010	-0.769	**
Landing angle (º)	0.065	0.062	0.069	**
$V_{parallel}$ (m/s)	0.041	0.033	0.050	**
Pop (m/s)	0.023	0.004	0.041	*

* Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.05$)

** Coefficient (beta-value) of independent factor significantly different from 0 ($p<0.001$)

Table 22: The proposed multiple regression model used to assess whether the $V_{parallel}$, the pop and landing angle was able to predict the EFH within skiers, and the change in the predicted EFH with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bound**	**CI higher bound**	
Constant	-1.068	-1.223	-0.913	**
Landing angle (º)	0.071	0.066	0.076	**
$V_{parallel}$ (m/s)	0.050	0.040	0.060	**
Pop (m/s)	0.028	0.005	0.052	*

* 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)

Table 23: The proposed multiple regression model used to assess whether the $V_{parallel}$, the pop and landing angle was able to predict the EFH within snowboarders, and the change in the predicted EFH with every increment of the independent variables (beta-value) with 95% confidence intervals (CI95% lower and higher bounds).

Independent variables	**Beta-value**	**CI lower bound**	**CI higher bound**	
Constant	-0.734	-0.919	-0.549	**
Landing angle (º)	0.060	0.054	0.066	**
$V_{parallel}$ (m/s)	0.034	0.021	0.047	**
Pop (m/s)	0.025	-0.006	0.056	

* 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)

5. Discussion

5.1 Pop

In this thesis we are investigating the pop performed by elite athletes in a World Cup slopestyle competition including three different jumps for ski and snowboard, its relation to factors that are related to performance and have been suggested to be related to injury risk (EFH). The observed values of pop ranged from -2.32 m/s to +2.20 m/s, with an average of +0.09 m/s (± 0.73). Hence, athletes are both reducing and increasing the take-off direction and, with this, also the take-off velocity at the point of take-off.

The body of scientific knowledge on pop is limited. McNeil (2012) reconstructed the pop for table-top jumps indirectly by matching jump distance and take-off speed, which is corresponding to the velocity component parallel to snow surface at take-off that was measured with photocells from the data by Shealy et al. (2010). McNeil (2012, p. 1) observed a poor relationship between velocity component parallel to snow surface at take-off and jump distance in the data of Shealy et al. (2010). Consequently, McNeil (2012, pp. 4 - 5) took the data of Shealy et al. (2010) and simulated how much pop (that was not included in the analysis by Shealy et al. (2010)) was needed to be added to the velocity component parallel to snow surface at take-off to match the flight distances. Based on this simulation McNeil (2012, p. 8) concluded that values of pop in that study ranged from -2.48 to +1.12 m/s. Obviously, the differences of the lower ranges between the pop found by McNeil (2012) and our observed pop do not differ much. Hence, it is possible that negative pop velocity components close to -2.5 m/s might either be close to representing the lower bound of what we will see athletes do in jumps like the ones used in Shealy et al. (2010) and our study. The upper range, however, is rather different, where we found pop values over +1 m/s larger that the values of McNeil. There could be several reasons for this difference.

Firstly, the jumps used in Shealy et al. (2010) and McNeil (2012) was of the type table-top, which has considered as less safe than both the roll-over and step-up which was used in this study (Norwegian Ministry of Culture and Equality, s.a.). Hence, the per se safer jump design might allow athletes to pop more without increasing the injury risk substantially in the Seiser Alm World Cup than in the recreational snowpark jumps that were used by Shealy (2010) and McNeil (2012).

Second, our study recorded athletes in a competition setting, where judging criteria dictate that higher and longer jumps (amplitude) and more spectacular tricks and rotations (difficulty and progression) are rewarded with more points. It is possible that athletes are more prone to try to exploit the possibility of pop to increase flight time in order to increase amplitude and difficulty in the sense of number of rotations that can be performed during aerial phase. Hence, if athletes feel safe on the roll-up and step-up jumps in Seiser Alm, they might try to find the limit of what is possible and/or safe enough with maximizing pop. Athletes in a recreational park on the table-top jump might not have the same reward to maximize pop, since they are not in a competition and because the table-top jump is per se considered as less safe.

Third, in the study of Shealy et al. (2010, p. 176) all athletes using the jumps in the terrain park were included and there was no control over the age, sex, experience level, etc. of the participants in the study. In this thesis, only elite athletes competing in the slopestyle World Cup in freestyle skiing or snowboarding were included. Since the population of Shealy et al. (2010) is unknown, we can only speculate in the spread and skill level of the athletes. However, it is likely that the skill level in the Shealy et al. (2010) study was lower than in the present study, which might also explain some of the difference in the sense that creating pop in take-off might be a demanding motor manoeuvre including physical and motor control skills that are likely better developed in World Cup level athletes compared to participants in a recreational park.

Fourth, there is also a methodological difference between the pop values from McNeil (2012) and this study. The pop values obtained by McNeil (2012) are obtained indirectly as he was determining the initial conditions of the take-off and adjusting the pop to fit the distance travelled while airborne, while we obtained and investigated the pop empirically and measured it directly as a position time derivate from true position data. McNeil (2012) on the other hand adjusts pop and implies that adding pop compensates for the jump distances alone, while in a real-life setting, air drag and lift could also account for differences in jump length and not pop alone.

Hence, considering that McNeil (2012) used an indirect method as a tool to determine pop based on some assumptions regarding air drag and lift and that the study was run on an unknown population, the pop values in this study reflect a true new contribution to the course builder community and academia. It is the first study reporting empirical measured values of pop for elite athletes competing in the World Cup ski and snowboarding. Furthermore, while previous research was unable to provide values for different groups of athletes, we investigated and present values of pop for men and women, ski and snowboard.

5.1.1 Jump specific differences in pop

Looking into the differences in the data between the three jumps (as presented in table 6, we found that there were differences in the pop performed between all of the jumps, where the average pop was found to be the highest in jump 1, followed by jump 2 and then jump 3. The mean pop in jump 1 was observed to be positive, at +0.46 m/s, which means that the athletes used the pop to increase the take-off direction and velocity at the point of take-off. Meanwhile, the mean pop was observed to be negative in jump 2, at – 0.16 m/s, and even lower in jump 3, at -0.41 m/s, meaning that athletes used the pop to reduce their take-off direction. This might be a response to the incline of the kicker at the point of take-off.

When investigating the course profile in figure 18, it can be observed that the incline of the kicker at the point of take-off was the flattest in jump 1, while jump 3 had the steepest incline. Hence, in this situation, lower values (or higher negative values) of pop were seen in jumps where the incline of the kicker was steeper, suggesting that there could exist a relationship between these factors where steeper inclines of the kickers are associated with lower values of pop. Furthermore, for some being negative, meaning that the pop is used to reduce the take-off direction. This hypothesis can further be supported by looking at the data of the $V_{parallel}$, a measurement used to assess the speed of the athletes at the moment of take-off. While the $V_{parallel}$ was lower in jump 1 than jump 2 and 3, no differences were found between jump 2 and jump 3. Yet, differences were observed in the performed pop between jump 2 and 3, supporting the idea that the athletes might use the pop to regulate the take-off direction based on the incline of the designed kicker at the point of take-off and the $V_{parallel}$ at take-off.

When investigating factors that might be related to pop either as a pre-condition or consequence between the jumps (table 6), we found differences in flight time between jump 1, 2 and 3. However, differences in the flight time are relatively small compared to the differences found the in the incline of the kicker at the take-off point and the $V_{parallel}$. Hence, it seems likely that a part of the pop performed by the athlete can be attributed as a measure to regulate the time the athlete is airborne, which is the time where the athletes can perform their manoeuvres. This possibility will be explored in more detailed later.

A difference was found in the horizontal jump distance between jump 1, 2 and 3. Not surprisingly, considering the lower $V_{parallel}$, athletes were observed to cover shorter horizontal distances while being airborne in jump 1 compared to both jump 2 and jump 3. However, if the $V_{parallel}$ was the only variable that could be connected to the jump distance, it does not explain why it was observed that the average jump distance was longer in jump 2 than jump 3. Another variable that showed a similar pattern between jump 2 and jump 3was in the pop, where a higher average of pop was found in jump 2 compared to jump 3 in positive direction. Hence, it is possible that both the $V_{parallel}$ and pop could lead to longer jump distances in horizontal direction between jumps. It is important to note, however, that the type of jump used in jump 3 is of the type step-up, where the design is different than the roll-over used in jump 1 and 2. The step-up is characterised by a deck with a higher arch, which could limit the jump distance somewhat (The Norwegian ministry of culture and equality, s.a.).

To investigate the proposed relation between the horizontal jump distance, $V_{parallel}$ and the pop, a multiple regression model was analysed, where the $V_{parallel}$ and the pop was used to try to predict the horizontal jump distance (table 8). Within all athletes (skiers and snowboarders), the model was considered as a significant predictor that was able to explain close to 60% of the variations in the horizontal jump distance, and where an increase in the pop of 1 m/s was found to increase the predicted output by 0.584m (CI95%: 0.199 – 0.969). Furthermore, an increase in 1 m/s in the $V_{parallel}$ was observed to increase the predicted output by 1.620 m (CI95%: 1.447 – 1.794), suggesting that both factors can influence the jump distance and furthermore that the pop can be used by the athletes to regulate their horizontal jump distance.

5.1.2 Pop within snowboard and skiing

The assessment of differences between skiers and snowboarders were performed on all jumps combined. Comparing the jumps in this study with the range of jumps built for competition and training, the jumps in this study can be considered to be somewhat similar of nature. Since equipment groups (skiers and snowboarders) are small for some of them, analysis was run across all three jumps.

Looking into the differences between freestyle skiers and snowboarders (table 7), skiers were observed to pop at an average of -0.078 m/s (± 0.723) and freestyle snowboarders an average of +0.296 m/s (± 0.679), leading to an average difference in pop where snowboarders were observed to pop +0.37 m/s more than skiers. However, when we look into the horizontal jump distance, it was observed that there were no differences found between the skiers and snowboarders. According to the International Ski and Snowboarding Federation (s.a.), landing in the sweet spot can be an indicator of a good amplitude in competitions, an area that are associated as the desired landing spot due to lower landing impacts (McNeil et al., 2012, p. 7). The multiple regression model suggested that athletes might use the pop and $V_{parallel}$ to regulate the jump distance. Following this logic, a possible explanation to why the snowboarders pop-ed more could be that the snowboarders approach the point of take-off with a lower $V_{parallel}$ and therefore have to pop more in order to make up for the lower $V_{parallel}$ to land in the sweet spot (as hypothesised in H6).

However, it was found that the $V_{parallel}$ was not different between the population of skiers and snowboarders, and hence, the difference found in the pop between ski and snowboard might not be performed to adjust for lack of $V_{parallel}$. This notion was further supported by the correlation found between the $V_{parallel}$ and the pop (figure 19). Within all athletes (skiers and snowboarders), the correlation was observed to be -0.458, while it was -0.536 within skiers and -0.328 within snowboarders. While the relationships were deemed significant, the strength of the correlation can be considered weak within snowboarders, and moderate within all athletes (skiers and snowboarders combined) and within the population of skiers (Fallowfield et al., 2005, p. 137). While this could suggest that there could be a negative relationship between the two variables, further inspection of the scatter plot in figure 19 suggests that the correlation might be somewhat weaker. Hence, these statistics weaken the hypothesis that athletes use the pop to overcome lower approaching velocities.

This further begs the question of why the snowboarders in average pops more in the positive direction compared to the skiers. Since no differences were found in flight time, horizontal jump distance and vertical jump height between skiers and snowboarders, this could suggest that the flight trajectory is altered between skiers and snowboarders during flight time, such that their trajectories get more and more similar despite different conditions in the take-off in terms of pop. Hence, it might be air drag and lift that alter the flight trajectories of skiers and snowboarders differently. Wolfsperger et al. (2021b, p. 1085) used a wind tunnel to assess the drag areas for freestyle skiers and snowboarders in different airborne postures and suggested using higher values of lift areas for skiers than for snowboarders in airborne postures. Furthermore, they found that the drag area due to vertical inflow (from below equipment) were higher in snowboarders and that both the posture and apparel had an influence the drag area, where more extended postures and wider fits were observed to increase the drag area (Wolfsperger et al., 2021b, p. 1085). Hence, it is possible that the drag area of snowboarders was higher than that of skiers due to them wearing looser apparel or having a posture that resulted in them having a higher drag area and/or a lower lift-drag ratio. Thus, it is possible that differences in the lift to drag ratio between skiers and snowboarders alter the trajectories during flight time such that they land around the same location despite differences in pop and similar $V_{parallel}$ at take-off, ultimately suggesting that the pop could be used as a measure to regulate the athlete's jump distance in order to land in the sweet spot and overcome differences in lift to drag ratio between skiers and snowboarders.

Air drag and lift are factors that are not derived for this thesis, and it is therefore uncertain whether these factors could explain the differences found in the pop. McNeil (2012, p. 6) hypothesised that the impact of air drag and lift in big air and slopestyle jumps are small for conditions with no or limited wind. Furthermore, for the speed and flight time the athletes have in slopestyle jumps compared to alpine skiing (Schindelwig et al., 2014) or ski jumping where a higher lift to drag ratio has been observed to correlate with jump distance for hill size of 140m, but not for hill size of 106m (Elfmark et al., 2022, pp. 3 – 4), suggesting that prolonged flight time increases the significance of lift to drag ratio for jump distance.

5.1.3 Pop within snowboarding, skiing and sex

The assessment of differences between skiers and snowboarders, female and male athletes were performed on all jumps combined. Comparing the jumps in this study with the range of jumps built for competition and training, the jumps in this study can be considered to be somewhat similar of nature. Since athlete groups (skiers and snowboarders, female and male, table 5) are small for some of them, analysis was run across all three jumps. The pop within female skiers was in average -0.29 m/s (± 0.71) and +0.07 m/s (± 0.71) for male skiers respectively (table 11), leading to an average difference of 0.36 m/s. A similar pattern was found within snowboarders, where the female snowboarders pop at an average of -0.17 m/s (± 0.66) and male snowboarders an average of +0.37 m/s (± 0.66), leading to an average difference of 0.54 m/s.

Similar to the differences between the population of skiers and snowboarders, there was no difference in the jump distance between female and male athletes in either skiers and snowboarders, suggesting that the pop was used to regulate the jump distance in order to land around the same landing point, that there are other reasons for performing a pop, or both. No differences were found in the $V_{parallel}$ at take-off or the landing. However, when inspecting the flight time, it was observed that the male skiers had a longer flight time than female skiers, and additionally, that the male snowboarders had longer flight times compared to female snowboarders. Hence, male athletes on average have a higher positive pop and longer flight times than their female counterparts, but the jump distance, and hence, landing location are the same.

Seeing that the athletes seem to take-off and land at the same position, if we were to follow the logic behind the gravity being a force that is exerted on the athlete and manipulating their trajectories equally in the negative vertical direction, it requires the arch of the male athletes to have a higher trajectory and a higher vertical jump height compared to their female counterparts within skiers and snowboarders. Further analysis also supports this notion, where the vertical jump height was found to be higher in male skiers than female skiers, and higher in male snowboarders than female snowboarders. One of the reasons an athlete would be interested in obtaining a longer flight time, while landing at the same distance, and thus, producing a higher vertical jump height, could be performance, where amplitude, difficulty and progression might be beneficial to acquire a higher score. A longer flight time can facilitate more time to perform manoeuvres and more time to orient their position in relation to the landing, and hence, the pop could be used as a measure to regulate the jump distance and flight time in order to enhance performance and safety.

5.1.4 Pop and performance

Following the Judges Guidebook for snowboard and freeski (International Ski and Snowboard Federation, 2019, pp. 10, 12 - 14), it is apparent that an increased amplitude (higher flight arch and longer flight time and distance) and difficulty and progression, and as part of that, the number of rotations, are critical to obtain a high score. Therefore, to investigate the relation between the pop and the variables associated with improved performance, it was investigated whether the athletes maximize their velocity $V_{parallel}$ and pop to increase flight time, as proposed in figure 1 (H1 and H2), and furthermore whether the long flight times was accompanied with higher average angular velocity to obtain a large number of rotations for the given flight time (H3 and H4), or if the athletes maximize amplitude in their jumps without maximizing the number of rotations. The multiple regression analysis assessing whether the flight time could be predicted by a model that consisted of the $V_{parallel}$ and the pop for all athletes (skiers and snowboarders) was significantly predicting the flight time, where an isolated increment in either the $V_{parallel}$ increased the predicted output of flight time (table 12). The explanatory rate of the model being 50% for all athletes and 55.5% for skiers and 45% for snowboarders, left room for other factors to explain the variance in flight time.

The number of rotations and average angular velocity was deployed as estimates of the complexity of the tricks performed (which could be related to the judging criteria difficulty and progression). The relation between the number of rotations, flight time and average angular velocity was hypothesised and visualised in figure 1, and follows a deterministic logic. It was confirmed empirically through the multiple regression model using the flight time and average angular velocity to predict the number of rotations (table 15) with very high explanatory power (98.4%) within all athletes (skiers and snowboarders combined). Both the flight time and average angular velocity were seen to separately increase the output of the number of rotations given that the other variable stays constant. Very similar results were also observed when the model was applied on the population of skiers and snowboarders separately (table 16 and 17), confirming the logic and suggesting that this is not exclusive for a single athlete group. Considering the logic and results of the multiple regression analysis, it is apparent that athletes do not pop exclusively to increase the flight time and amplitude, but simultaneously use the pop to increase the flight time in order to generate more rotations and increase the complexity of their aerial manoeuvres.

Now, maximizing the pop in the direction normal to the surface of the kicker and the generation of angular momentum around the axis normal to the snow surface of the kicker might be demanding, and it might be possible that one of these actions would limit the other (H7). As can be seen in Equation 5, the angular momentum is determined as the product of the moment of inertia and the angular velocity. As the moment of inertia and the angular momentum was not measured in this analysis, the average angular velocity will be used as an indirect measurement of the angular momentum.

First, the relationship between the $V_{parallel}$ and the average angular velocity was investigated (as hypothesised in H5). The Spearman’s rho-test was performed to investigate this relationship, both within all athletes (skiers and snowboarders combined), within skiers, and within snowboarders (figure 22). Results showed that it was not possible to find any significant correlation between the $V_{parallel}$ and the average angular velocity within all athletes (skiers and snowboarders combined), skiers or snowboarders separately. Hence, it is unlikely that the $V_{parallel}$ limits the generation of angular momentum, weakening our hypothesis.

The relationship between the pop and the average angular velocity (figure 23) was investigated using a Spearman’s rho-test which turned out being significant, but weak for (0.330) for all athletes (skiers and snowboarders combined) and within skiers (0.201), but with a moderate relation (0.525) for snowboarders (Fallowfield et al., 2005, p. 137). Hence, it is evident that the pop does not have a limiting influence on the generation of average angular velocity through generation of angular momentum in take-off, but rather, there is a tendency towards it being possible that an increase in the angular momentum is somewhat positively correlated with an increase in the pop, especially in snowboarders.

Angular momentum is generated through the generation of torque between ski/snowboard and the snow surface, and hence, it is plausible that the generation of high torque also requires the generation of a high ground reaction force. Hence, on the contrary, it is possible that the opposite of our hypothesis could be true where pop and average angular velocity are increasing simultaneously in our data, suggesting that the generation of torque might require increased normal forces to the snow surface in order to generate sufficient friction between equipment and snow to generate the torque needed to establish a large angular momentum. Seeing that the correlation was stronger within snowboarders could indicate that this is especially prominent in snowboarders where the athlete's stance and connection to the equipment might make it more challenging to generate torque than for skiers. However, this is only speculation based on a correlation between two independent factors, and thus, future research is needed in order to either refute or confirm this notion.

5.1.5 Pop and its impact on equivalent fall height

In our study EFH was observed to have a median of 0.47m (IQR: 0.29) and ranged from 0.04m to 1.37m for all athletes (skiers and snowboarders) in all jumps combined. Compared with the proposed human and reference limit for EFH of 1.5m (Minetti et al., 1998, p. 1789; McNeil et al., 2012, p. 8; US Terrain Park Council, 2017 as cited by Petrone et al., 2017, p. 290), the EFH of all athletes (skiers and snowboarders combined) were within this limit. However, as Scher et al. (2015, p. 86, 80 - 83) specify, the likelihood of injuries occurring at EFH lower than this reference is still present, and hence, a reduced EFH does not imply absence of injury risk.

Hubbard & Swedberg (2012, p. 88) found that EFH was substantially reduced if pop was absent (compared to the assumed maximum conceivable pop). Considering these results and the logic of McNeil (2012, p. 10), who proposed that "the EFH scales as the takeoff speed squared and is roughly proportional to the sine of the takeoff angle." (McNeil, 2012, p. 10), a multiple regression model using the $V_{parallel}$ and pop to predict EFH was proposed and applied on all athletes (skiers and snowboarders) (H8 and H9). The model (table 18) significantly predicted the EFH, but the model could only explain 6.6% of the variation that was found in the EFH, which is very low and not in line with the hypothesis formed based on the notion of McNeil (2012).

Before performing any changes to the model, it was applied to the population of skiers and snowboarders separately, in order to investigate whether the individual difference in pop between the two populations had an influence on the variation. While the model was significant (table 19 and 20), the explanatory power was approximately as low as for the entire group. Thus, this suggests that it is necessary to provide more information to the model in order for it to better explain the variation observed in the EFH.

If we have a linear landing surface that have a constant surface angle, it would be reasonable to assume that the EFH would increase with increased pop and $V_{parallel}$, following the logic of McNeil (2012). However, when looking at the course profile figure 18, it is apparent that this is not the case. Another variable that has been observed to be associated with smaller EFH is the landing angle (as can be seen in Equation 3), where the smaller the difference between the angle of the trajectory's velocity vector and surface angle in the landing, the smaller EFH will be for a given velocity (Hubbard, 2009, p. 178; Böhm & Senner, 2009, p. 173; McNeil et al., 2012, p. 6).

Based on this premise, a new model was proposed where the $V_{parallel}$ and the pop was used along with the landing angle to predict the EFH within all athletes (skiers and snowboarders) combined (table 21). This model was found to be a significant predictor of the EFH, where the Vparallel, the pop and the landing angle explained 82.3% of the variation in EFH, which is a large improvement of explanatory power. The predicted EFH increased by 0.023m per 1 m/s (CI95%: 0.004 – 0.041) of increase in the pop, given that the landing angle and $V_{parallel}$ stay constant. Thus, including all athletes (skiers and snowboarders, men and women) in one group and assessing this relationship supports the statement of McNeil (2012, p. 10), that an increase in the pop (and $V_{parallel}$) would increase the EFH. Furthermore, the big increase in the explanatory rate of the model suggests that designing landing areas where the snow surface angles are adjusted for the possible COM-trajectories could minimize the landing angles, and hence, landing impact, which is good news for jump design possibilities.

The same regression model was applied for the population of skiers and snowboarders separately (table 22 and 23), and both models were significant predictors of the EFH, with an explanatory power of 85.9% within skiers and 79.6% within snowboarders. Within skiers, the coefficients of the $V_{parallel}$, the pop and the landing angle stayed significantly different from zero, meaning that an increase in either would increase the output (as the coefficient was observed to be positive). However, for snowboarders, while the coefficient of the landing angle and the $V_{parallel}$ was significantly different from zero (in the positive direction), the coefficient of the pop was not. In other words, even if the landing angle and the $V_{parallel}$ stay constant, it is uncertain whether an increase in the pop would lead to an increase, decrease or no change at all in the EFH.

Following these results, a couple possible explanations could be extracted; 1) the notion of McNeil (2012) was not in line with our data within snowboarders, or 2) there were uncontrolled variables that could help explain the variation in the pop and EFH in our data. Considering that an increase in the pop was seen to increase the predicted EFH when investigating all athletes combined and within skiers, and that the explanatory rate of the model within snowboarders were lower, the latter is more likely. Previously, we surmised that the differences found in the pop between the skiers and snowboarders could be explained by the ratio between the air lift and drag, which are variables not calculated in this thesis that influence the COM-trajectories while airborne. While the wind was rather constant and below 3 m/s most of the time, and hence, not likely influencing the results substantially, it is possible that variation in wind between runs and variations in drag area and lift area following variations in apparel and postures might explain part of the variations that we see in the EFH. Thus, quantifying the effect of air drag and lift will help pinpointing the effect of pop on EFH more accurately than what we were able to in this thesis.

5.2 Limitations/Method

5.2.1 COM annotation

As presented in figure 14 it was evident that the woods in the background presented some challenges to the annotation process and it was difficult to discern the athlete from the background in a multitude of images while the athlete was airborne. During the phases when the CV algorithms was unable to annotate the athlete, a lot of effort was put into the solution of this problem by manual inspection of the annotated data, followed by manual annotation by human raters. The threat to inter-rater reliability by several raters was met with a learning and consolidation process, where raters were trained on the same dataset and compared to generate and ensure a common understanding of where to annotate the COM in the image.

5.2.2 Small sample in some groups

From the 1248 recorded jumps, 273 passed the quality criteria and were used for the analysis. Considering that many recorded jumps were excluded, the statistical power was reduced and more effort should be spent to improve the quality of the recorded jumps to allow inclusion of a larger portion of the recorded data. The main shortcoming was that athletes were hidden behind the kicker before take–off and were only visible from the lateral camera. However, strict exclusion criteria can also be considered a strength in terms of reliability and validity within the included data. The exclusion of runs reduced the statistical power of the groups, especially female snowboarders. For female snowboarders, we only had a total of 22 jumps available over all jumps combined, where there were only 5 and 6 recordings available for analysis from jump 2 and jump 3 respectively. There is a possibility that this have had an influence on the outcome for the analysis of the differences between female and male athletes within snowboarders. Furthermore, a larger dataset would allow to run analysis on the three different jumps and provide more insight into the effect of the differences between these jumps.

5.2.3 Indirect measures of injury risk and performance

In this study, no data was gathered that directly measures the number of injuries the athletes sustained or the actual performance of the athletes. Hence, while the theory and results might point at the pop being used as a measure to enhance the performance of the athletes, the data do not allow to establish a direct link to performance. The reason for the lacking performance data is that performance in slopestyle is only assessed for the entire jump section with three consecutive jumps, and hence, linking the pop in one jump cannot be linked to competition judging. The same is true for injury risk. It was suggested by the literature that EFH is associated with an increased injury risk (Hubbard & Swedberg, 2012, p. 79; McNeil, 2012, p. 2; McNeil et al., 2012, p. 8; Levy et al., 2015, p. 14), where higher values of EFH would indicate higher impacts that must be absorbed in the landing. However, as we have presented in the theory, injury risk could be a complex phenomenon and injuries have been observed to arise following a multitude of different reasons and situations, and thus, a higher EFH does not directly imply increased injury risk.

5.3 Acknowledgements

This master is a part of the long-term injury project issued by the IOC, where the mission is to protect the athlete's health by preventing injuries and making the conditions surrounding future events safer for the athletes.

5.4 Conclusion

In this thesis we investigated ranges of ‘pop’ on typical jumps for elite athletes (women, men, ski and snowboard) competing in the slopestyle World Cup. On the 273 recorded runs passing the exclusion criteria, the measured trials ranged from -2.32 m/s to +2.20 m/s, where athletes used pop both to reduce and increase their take-off direction. Female skiers pop-ed at a mean of -0.29 m/s (± 0.71), while male skiers pop-ed at a mean of +0.07 m/s (± 0.71), female snowboarders at a mean of -0.17 m/s (± 0.66) and male snowboarders at a mean of +0.37 m/s (± 0.66). Pop seems to be used to regulate jump length, to optimize landing impact. Pop was used to extend flight time to increase amplitude and allow for a higher number of rotations. The generation of more pop in order to extend flight time seems not to hamper the generation of angular momentum in take-off, since flight time and average angular velocity increased simultaneously. All athletes landed at the same distance and had similar velocities components parallel to the snow surface at the kicker. Since snowboarder pop-ed more than skiers and males pop-ed more than females, resulting in longer flight time and higher vertical jump height for males. The effect of pop on EFH was smaller than suggested in earlier studies and depended on the landing angle.

As far as we know, we are the first to empirically measure ranges of pop performed by elite athletes, both for males, females, skiers and snowboarders, which can give valuable insights into why and how the pop is used by World Cup athletes. The data and relations could be used to facilitate computer simulation to assist in jump planning and construction.

However, there are variables not derived for in this this thesis, such as air drag and lift, that possibly could explain some of the variation and differences observed. Future research should focus on including such variables and broaden the spectre of different types of jumps to establish a broader understanding of the role of pop for all user groups.

Litterature

Bahr, R., & Krosshaug, T. (2005). Understanding injury mechanisms: a key component of preventing injuries in sport. *British Journal of Sports Medicine, 39*(6), 324–329. https://doi.org/10.1136/bjsm.2005.018341

Böhm, H., & Senner, V. (2009). Safety in big jumps: Relationship between landing shape and impact energy determined by computer simulation. *ASTM Special Technical Publication, 1510*, 165–174. https://doi.org/10.1520/STP47479S

Bradski, G., & Kaehler, A. (2016). *Learning OpenCV 3: computer vision in C++ with the OpenCV library*. O'Reilly Media, Inc.

Brettforbundet. (s.a.). *Norgescup*. Retrieved May 4, 2022, from https://www.brettforbundet.no/snow/events/norgescup#ranking-og-resultater

Bright, T. (2020). Snowboarding. In *Britannica*. Retrieved May 4, 2022, from https://www.britannica.com/sports/snowboarding

Burkett, & Carr, G. A. (2019). *Applied sport mechanics* (4th ed., pp. IX, 253). Human Kinetics.

Bürki, B., Guillaume, S., Sorber, P., & Oesch, H. (2010). DAEDALUS: A versatile usable digital clip-on measuring system for Total Stations. *2010 International Conference on Indoor Positioning and Indoor Navigation,* 1–10. https://doi.org/10.1109/IPIN.2010.5646270

Carr. (1997). *Mechanics of sport : a practitioner's guide* (pp. X, 213). Human Kinetics.

Charalampous, E., Psimoulis, P., Guillaume, S., Spiridonakos, M., Klis, R., Bürki, B., Rothacher, M., Chatzi, E., Luchsinger, R., & Feltrin, G. (2015). Measuring sub-mm structural displacements using QDaedalus: a digital clip-on measuring system developed for total stations. *Applied Geomatics*. *7*, 91 – 101. https://doi.org/10.1007/s12518-014-0150-z de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov’s segment inertia parameters. *Journal of Biomechanics, 29*(9), 1223–1230. https://doi.org/https://doi.org/10.1016/0021-9290(95)00178-6

Ehrnthaller, C., Kusche, H., & Gebhard, F. (2015). Differences in injury distribution in professional and recreational snowboarding. *Open Access Journal of Sports Medicine*, *6*, 109–119. https://doi.org/10.2147/OAJSM.S78861

Elfmark, O., Ettema, G., Groos, D., Ihlen, E. A. F., Velta, R., Haugen, P., Braaten, S. & Gilgien, M. (2021). Performance analysis in ski jumping with a differential global navigation satellite system and video-based pose estimation. *Sensors, 21(16),* 5318. https://doi.org/10.3390/s21165318

Elfmark, O., Ettema, G., & Gilgien, M. (2022). Assessment of the steady glide phase in ski jumping. *Journal of Biomechanics*, *139,* 111139. https://doi.org/https://doi.org/10.1016/j.jbiomech.2022.111139

Engebretsen, L., Steffen, K., Alonso, J. M., Aubry, M., Dvorak, J., Junge, A., Meeuwisse, W., Mountjoy, M., Renstrom, P., & Wilkinson, M. (2010). Sports injuries and illnesses during the Winter Olympic Games 2010. *Br J Sports Med*, *44*(11), 772–780. https://doi.org/10.1136/bjsm.2010.076992

Fallowfield, Hale, B. J., & Wilkinson, D. M. (2005). *Using statistics in sport and exercise science research* (pp. vi, 370). Lotus Publishing.

Fastovets, M., Guillemaut, J., Hilton, A. (2013. 23 – 28 September). *Athlete Pose Estimation from Monocular TV Sports Footage*. Proceedings of the 2013 IEEE Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), Portland, OR, USA, pp. 1048 – 1054. https://doi.org/10.1109/CVPRW.2013.152

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

Flørenes, T. W., Nordsletten, L., Heir, S., & Bahr, R. (2012). Injuries among World Cup ski and snowboard athletes. *Scandinavian Journal of Medicine & Science in Sports, 22*(1), 58–66. https://doi.org/https://doi.org/10.1111/j.1600-0838.2010.01147.x

Fuller, C. W., Ekstrand, J., Junge, A., Andersen, T. E., Bahr, R., Dvorak, J., Hägglund, M., McCrory, P., & Meeuwisse, W. H. (2006). Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Scandinavian Journal of Medicine & Science in Sports, 16*(2), 83–92. https://doi.org/10.1136/bjsm.2005.025270

Gilat, A., & Subramaniam, V. (2014). *Numerical methods for engineers and scientists: An introduction with applications using MATLAB* (3rd ed.). Jon Wiley & sons Inc.

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., & Müller, E. (2015). Characterization of course and terrain and their effect on skier speed in World Cup alpine ski racing. *PLoS One, 10*(3), e0118119. 1 - 25. https://doi.org/10.1371/journal.pone.0118119

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., & Müller, E. (2018). Application of dGNSS in alpine ski racing: Basis for evaluating physical demands and safety. *Frontiers in Physiology, 9*(MAR), 145. 1 – 11. https://doi.org/10.3389/fphys.2018.00145

Guillaume, S., Buerki, B., & Griffet, S. (2012, 6 – 10 May). *QDaedalus : Augmentation of Total Stations by CCD Sensor for Automated Contactless High-Precision Metrology*. FIG Working Week 2012, Rome, Italy. https://www.fig.net/resources/proceedings/fig_proceedings/fig2012/papers/ts09i/TS09I_guillaume_buerki_et_al_6002.pdf

He, K., Zhang, X., Ren, S., & Sun, J. (2016, 27 – 30 June). *Deep residual learning for image recognition*. Proceedings of the 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 770–778, Las Vegas, NV, US. https://doi.org/10.48550/arXiv.1512.03385

Henrie, M., Petron, D., Pepper, M., Kirkham, J., Chen, Q., & Willick, S. (2010). Comparison of Ski and Snowboard Injuries that Occur Inside Versus Outside Terrain Parks: 2001: *Medicine & Science in Sports & Exercise*, *42*(5), 473–474. https://doi.org/10.1249/01.MSS.0000385054.56383.47

Hirt, C., Guillaume, S., Wisbar, A., Bürki, B., & Sternberg, H. (2010). Monitoring of the refraction coefficient in the lower atmosphere using a controlled setup of simultaneous reciprocal vertical angle measurements. *Journal of Geophysical Research: Atmospheres*, *115*(D21). https://doi.org/https://doi.org/10.1029/2010JD014067

Hubbard, M. (2009). Safer ski jump landing surface design limits normal velocity at impact. *Skiing Trauma and Safety (ASTM STP 1510)*, *17,* 175 - 183. https://doi.org/ 10.1520/JAI101630

Hubbard, M., & Swedberg, A. (2012). Design of Terrain Park jump landing surfaces for constant equivalent fall height is robust to "Uncontrollable" factors. In R. J. Johnson, J. E. Shealy, R Greenwald, I. Scher (Eds.), *Skiing trauma and safety: 19th volume (75 – 94).* ASTM International. https://doi.org/ 10.1520/STP104515

International Ski and Snowboard Federation. (2019, June). *Judges Handbook: Snowboard and Freeski*. FIS. Retrieved May 4, 2022, from https://assets.fis-ski.com/image/upload/v1610953451/fis-prod/assets/FIS_SB_FK_JudgesHandbook_20_21.pdf

International Ski and Snowboard Federation. (2021, 17th December). *Book VI: Join Regulations for Snowboard / Freestyle Ski / Freeski*. FIS. Retrieved May 4, 2022 from https://assets.fis-ski.com/image/upload/v1639771459/fis-prod/assets/SBFSFK_NEW_ICR_clean_winter_2021.pdf

Junge, A., Engebretsen, L., Alonso, J. M., Renström, P., Mountjoy, M., Aubry, M., & Dvorak, J. (2008). Injury surveillance in multi-sport events: the International Olympic Committee approach. *British Journal of Sports Medicine*, *42*(6), 413–421. https://doi.org/10.1136/bjsm.2008.046631

Junge, A., Engebretsen, L., Mountjoy, M. L., Alonso, J. M., Renström, P. A. F. H., Aubry, M. J., & Dvorak, J. (2009). Sports injuries during the summer Olympic Games 2008. *The American Journal of Sports Medicine*, *37*(11), 2165–2172. https://doi.org/10.1177/0363546509339357

Levy, D., Hubbard, M., McNeil, J. A., & Swedberg, A. (2015). A design rationale for safer terrain park jumps that limit equivalent fall height. *Sports Eng*, *18*, 1–13. http://dx.doi.org/10.1007/s12283-015-0182-6

Lin, T.-Y., Dollár, P., Girshick, R., He, K., Hariharan, B., & Belongie, S. (2017, 21 – 26 July). *Feature pyramid networks for object detection*. Proceedings in the 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), pp. 936 – 944, Honolulu, HI, USA. https://doi.org/10.1109/CVPR.2017.106

Lind, D., & Sanders, S. P. (2004). *The physics of skiing : skiing at the triple point* (2nd ed.). Springer.

Link, J., Guillaume, S., & Eskofier, B. M. (2021). Experimental Validation of Real-Time Ski Jumping Tracking System Based on Wearable Sensors. *Sensors*, *21*(23). https://doi.org/10.3390/s21237780

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://pubmed.ncbi.nlm.nih.gov/33414860

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. *British Journal of Sports Medicine*, *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. (2012). Modelling the “Pop” in winter terrain park jumps. In R. J. Johnson, J. E. Shealy, R Greenwald, I. Scher (Eds.), *Skiing trauma and safety: 19th volume* (95 - 119*).* ASTM International. https://doi.org/10.1520/STP104240

McNeil, J. A., Hubbard, M., & Swedberg, A. (2012). Designing tomorrows 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 LB-1028), 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

Norwegian Ministry of Culture and Equality. (s.a.). *Designe en snowpark*. Retrieved May 4, 2022, from https://snowpark.no/designe-en-snowpark/

Norwegian Ski Federation. (s.a.-a). *Slopestyle*. Retrieved May 4, 2022, from https://www.skiforbundet.no/fagportal/anleggsweb/freeski-og-freestyle/freeski/slopestyle/

Norwegian Ski Federation. (s.a.-b). *Big Air*. Retrieved May 6, 2022, from https://www.skiforbundet.no/fagportal/anleggsweb/freeski-og-freestyle/freeski/big-air/

Ogawa, H., Sumi, H., Sumi, Y., & Shimizu, K. (2009). Skill Level-Specific Differences in Snowboarding-Related Injuries. *The American Journal of Sports Medicine*, *38*(3), 532–537. https://doi.org/10.1177/0363546509348763

Ostrek, M., Rhodin, H., Fua, P., Müller, E., & Spörri, J. (2019). Are existing monocular computer vision-based 3d motion capture approaches ready for deployment? a methodological study on the example of alpine skiing. *Sensors*, *19*(19), 4323. https://doi.org/10.3390/s19194323

Parmar, P., & Morris, B. (2019, 7 – 11 January). *Action Quality Assessment Across Multiple Actions*. Proceedings in the 2019 Winter Conference on Applications of Computer Vision (WACV), pp. 1468 – 1476, Waikoloa Village, HI, USA. https://doi.org/10.1109/WACV.2019.00161

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

Rhodin, H., Spörri, J., Katircioglu, I., Constantin, V., Meyer, F., Müller, E., Salzmann, M., & Fua, P. (2018, 18 – 23 June). *Learning Monocular 3D Human Pose Estimation from Multi-view Images*. Proceedings of the 2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPRW), pp. 8437 – 8446, Salt Lake City, UT, USA. https://doi.org/10.1109/CVPR.2018.00880

Scher, I., Shealy, J., Stepan, L., Thomas, R., & Hoover, R. (2015). Terrain park jump design: would limiting equivalent fall height reduce spine injuries? In R. J. Jognson, J. E. Shealy, R. M. Greenwald (Eds.), *Skiing Trauma and Safety: 20th Volume* (72 – 92). ASTM International.

Schindelwig, K., Platzer, H. P., Mössner, M., & Nachbauer, W. (2019). Safety recommendations of winter terrain park jumps into airbags. *Journal of Science and Medicine in Sport*, *22,* S50 – S54. https://doi.org/10.1016/j.jsams.2018.09.229

Schindelwig, K., Reichl, W., Kaps, P., Mössner, M., & Nachbauer, W. (2014). Safety assessment of jumps in ski racing. *Scandinavian Journal of Medicine & Science in Sports*, *25(6),* 797 - 805. https://doi.org/10.1111/sms.12300

Schmölzer, B., & Müller, W. (2002). The importance of being light: aerodynamic forces and weight in ski jumping. *Journal of Biomechanics*, *35*(8), 1059–1069. https://doi.org/10.1016/S0021-9290(02)00066-0

Shapiro, L. G. (2001). *Computer vision* (G. C. Stockman, Ed.). Prentice Hall.

Shealy, J. E., Scher, I., Stepan, L., & Harley, E. (2010). Jumper kinematics on terrain park jumps: relationship between takeoff speed and distance traveled. In R. J. Johnsen, J. E. Shealy, V. Senner (Eds.), *Skiing Trauma and Safety, 18th volume* (173 – 186). ASTM International.

Skaloud, J., & Limpach, P. (2003, 9 – 12 September). *Synergy of CP-DGPS, Accelerometry and Magnetic Sensors for recise Trajectography in Ski Racing*. Proceedings in the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS/GNSS), Portland, OR, USA. https://www.semanticscholar.org/paper/Synergy-of-CP-DGPS%2C-Accelerometry-and-Magnetic-for-Skaloud-Limpach/51ab5a51cbe654e4f33369f6700be2b9ee4a8fc6

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 - 449. https://doi.org/10.1136/bjsports-2014-094538

Spörri, J., Schiefermüller, C., & Müller, E. (2016). Collecting Kinematic Data on a Ski Track with Optoelectronic Stereophotogrammetry: A Methodological Study Assessing the Feasibility of Bringing the Biomechanics Lab to the Field. *PloS One*, *11*(8), e0161757. https://doi.org/10.1371/journal.pone.0161757

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. *British Journal of Sports Medicine*, *48*(1), 41 - 45. https://doi.org/10.1136/bjsports-2013-093145

Sternheim, M. M. (1991). *General physics* (J. W. Kane, Ed.; 2nd ed.). Wiley & Sons.

Tarazi, F., Dvorak, M., & Wing, P. (1999). Spinal injuries in skiers and snowboarders. *The American Journal of Sports Medicine*, *27*(2), 177–180. https://doi.org/10.1177/03635465990270021101.

The International Olympic Committee. (s.a.-a). *Freestyle skiing*. Olympic. Retrieved May 3, 2022, from https://olympics.com/en/sports/freestyle-skiing/

The International Olympic Committee. (s.a.-b). *Snowboard*. Olympic. Retrieved May 3, 2022, from https://olympics.com/en/sports/snowboard/

Thomas, G., Gade, R., Moeslund, T. B., Carr, P., & Hilton, A. (2017). Computer vision for sports: Current applications and research topics. *Computer Vision and Image Understanding*, *159*, 3–18. https://doi.org/10.1016/j.cviu.2017.04.011

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

Toth, G., & Volgyesi, L. (2019). *Experiences of QDaedalus Measurements, 6(9)*. 75–86.

van Mechelen, W., Hlobil, H., & Kemper, H. (1992). Incidence, Severity, Aetiology and Prevention of Sports Injuries. *Sports Medicine*, *14*(2), 82–99. http://doi.org/10.2165/00007256-199214020-000021

van Tiggelen, D., Wickes, S., Stevens, V., Roosen, P., & Witvrouw, E. (2008). Effective prevention of sports injuries: a model integrating efficacy, efficiency, compliance and risk-taking behaviour. *Br J Sports Med*, *42*(8), 648–652. https://doi.org/10.1136/bjsm.2008.046441

Vosselman, G. (2001). Semi-automatic CAD based Reconstruction of Industrial Installations. *KI*, *15*, 23–27. https://www.researchgate.net/profile/George-Vosselman/publication/220634199_Semi-automatic_CAD_based_Reconstruction_of_Industrial_Installations/links/0c960524c7203ed118000000/Semi-automatic-CAD-based-Reconstruction-of-Industrial-Installations.pdf

Willmott, T., & Collins, D. (2015). Challenges in the transition to mainstream: promoting progress and minimizing injury in freeskiing and snowboarding. *Sport in Society*, *18*(10), 1245–1259. https://doi.org/10.1080/17430437.2015.1031530

Wolfsperger, F., Meyer, F., & Gilgien, M. (2021a). The Snow-Friction of Freestyle Skis and Snowboards Predicted From Snow Physical Quantities. *Frontiers in Mechanical Engineering*, *7*. https://doi.org/10.3389/fmech.2021.728722

Wolfsperger, F., Meyer, F., & Gilgien, M. (2021b). Towards more valid simulations of slopestyle and big air jumps: Aerodynamics during in-run and flight phase. *Journal of Science and Medicine in Sport*, *24*, 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*. Retrieved 28. June, 2022, from https://github.com/facebookresearch/detectron2

Zhang, F., Zhu, X., & Ye, M. (2019, 15 – 20 June). *Fast human pose estimation*. Proceedings of the 2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), pp. 3517–3526, Long Beach, CA, USA. https://openaccess.thecvf.com/content_CVPR_2019/papers/Zhang_Fast_Human_Pose_Estimation_CVPR_2019_paper.pdf

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3D	Three-dimentional
CI	Confidence interval
COM	Centre of mass
CV	Computer vision
EFH	Equivalent fall height
IOC	The International Olympic Committee
IQR	Interquatile range
$V_{parallel}$	Velocity parallel to the snow surface

Appendix

Appendix 1: 1 Hz wind measurements taken during competition days.

Appendix 2: Scatter plot of the range and individual values within the three jumps.

Appendix 1: 1 Hz wind measurements taken during competition days

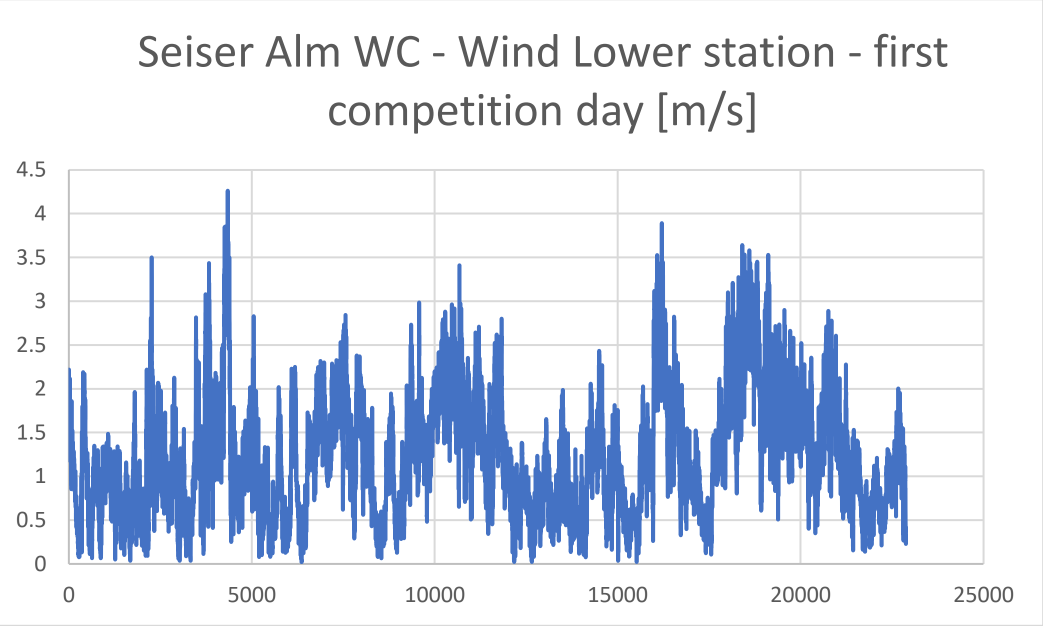

Figure 1: Wind measurements at the first competition day of the slopestyle World Cup in Seiser Alm, Italy, measured at 1Hz.

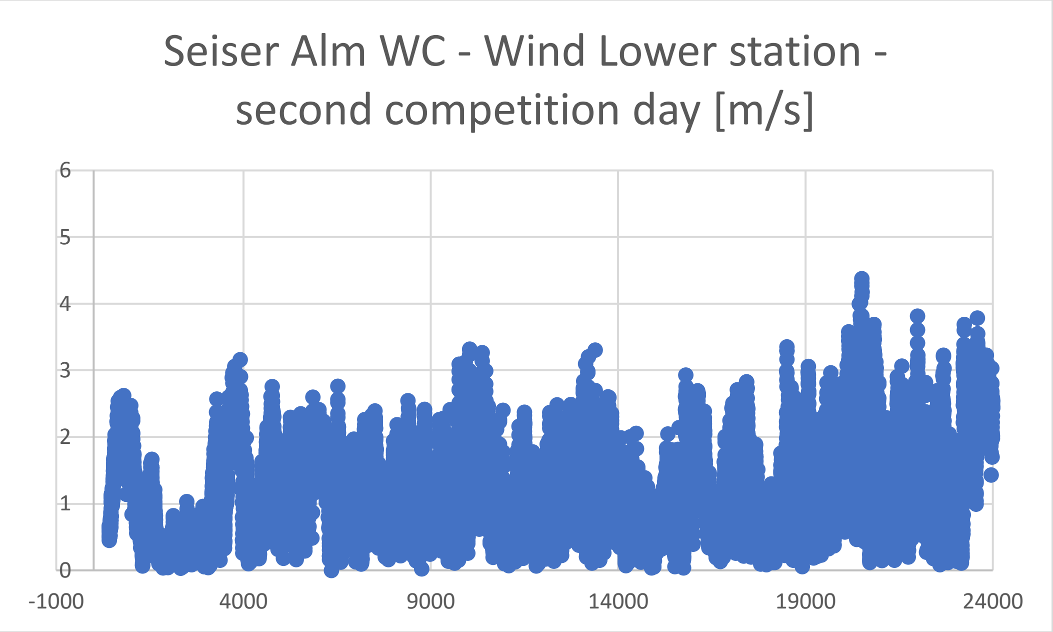

Figure 2: Wind measurements at the second competition day of the slopestyle World Cup in Seiser Alm, Italy, measured at 1Hz.

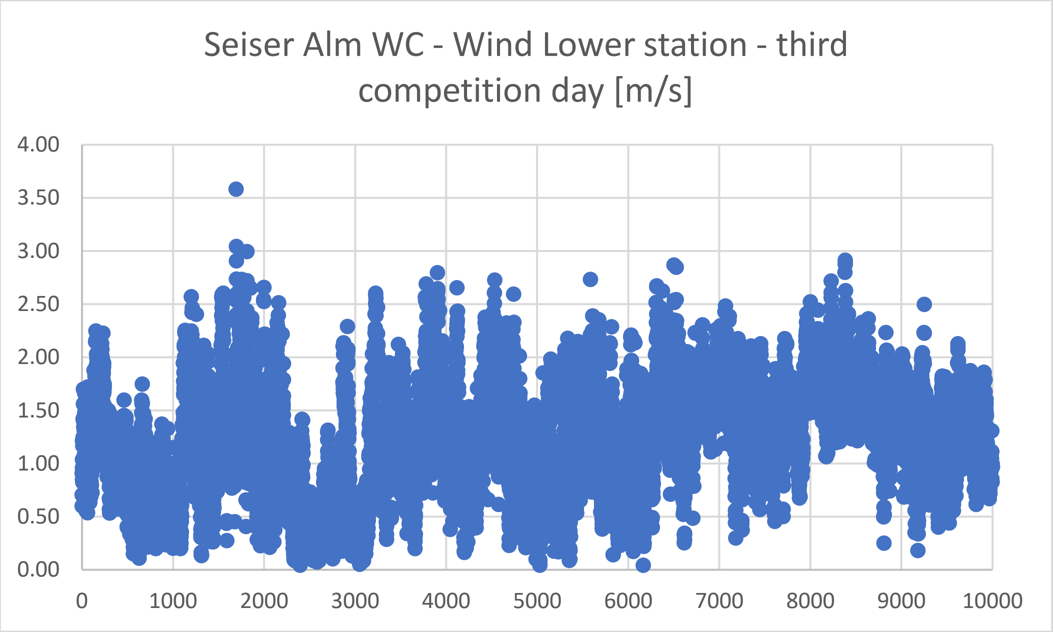

Figure 3: Wind measurements at the third and final competition day of the slopestyle World Cup in Seiser Alm, Italy, measured at 1Hz.

Appendix 2: Scatter plot of the range and individual values of pop within the three jumps.

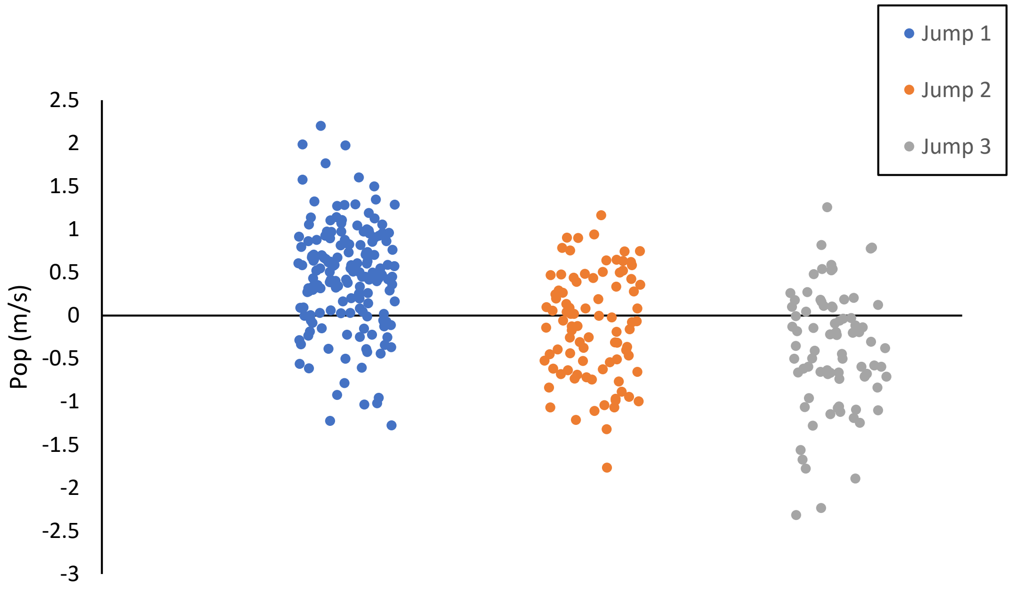

Figure 1: Scatter plot showing the range and individual pop values within jump 1 (blue dots), jump 2 (orange dots), and jump 3 (grey dots).