Sport specific strength in alpine competitive skiing

- What characterizes alpine elite skiers?

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Abstract

Introduction: Alpine skiing has changed since the 1990s and it is unclear what sport specific strength is within modern alpine elite skiing. Purpose: The aim of this study was to create a strength profile and to investigate what sport specific strength is within alpine elite skiers.

Method: A total number of 24 participant took part in this cross-sectional study, where eleven alpine elite skiers were compared with thirteen well-trained strength athletes with different sports background. The participants were tested in squat jump (SJ), counter movement jump (CMJ), drop jump (DJ) as well as isometric, isokinetic concentric and isokinetic eccentric strength with different dynamic velocities. In addition to these tests, reaction strength index (RSI) and eccentric utilization ratio (EUR) were calculated. Correlation analyses were performed to investigate if there were any relationships between the jump test variables and the isometric and eccentric strength tests. Results: The SKI group jumped higher in relation to their bodyweight (BW) in SJ (P>0,01), CMJ (P>0,05) and DJ (P>0,01). The SKI group also showed significantly higher RSI values (P>0,05). For the strength tests, the SKI group performed significantly better in all the eccentric velocities (P>0,05), the isometric test (P>0,01) and in the slowest concentric velocity (P>0,01). The SKI group showed significantly higher strength values (P>0,05) in relative isometric strength with knee angles between 20°-60°, where the largest significant difference appeared at 25° (P>0,001). No significant differences were found in the absolute values in either the jump or the strength tests. Only moderate (r=0,30-0,49) significant (P>0,05) correlations were found between the fastest eccentric tests and the SJ and DJ within all athletes. No significant correlations were found within the SKI group alone. Conclusion: This study presented evidence that sport specific strength for alpine elite skiers may primarily consist of isometric strength, training in slow concentric velocities and general eccentric training. The results indicate that the sport specific strength for alpine elite skiers does not include concentric training in moderate and fast concentric movements.
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1 Introduction

Alpine ski racing has been an Olympic sport since 1936 and is one of the most popular winter sports in the world. Alpine skiing consists of the two technical disciplines, slalom (SL) and giant slalom (GS), and the two speed disciplines, super-g (SG) and downhill (DH) (Turnbull et al., 2009). Lately also the parallel slalom (PSL) has become a popular discipline and has been a part of the Olympic games since PyeongChang 2018 (The Swedish Olympic Committee, 2021). The duration of a single run in the technical event is between 45-90 seconds and as long as up to 2-3 minutes in the speed events (Ferguson, 2010) where the velocities can be as high as 130 km/h (Turnbull et al., 2009).

To enhance performance in alpine skiing the skier needs to maintain the highest possible velocity while minimizing the energy dissipation and skiing an optimal trajectory in the course (Hébert-Losier et al., 2014). Further the skier also needs to minimize the aerodynamic drag and the friction between the skis and the snow (Supej & Holmberg, 2019). These factors limit the performance during a run, where the main goal is to minimize the energy dissipation in every turn (Hébert-Losier et al., 2014). It is common that the turn is divided into individual phases (initiation, steering and completion phase) where the steering phase normally is divided into another two phases (steering 1 and steering 2), see figure 1 (Falda-Buscaiot et al., 2017; Kröll et al., 2015). A training day can contain up to 400 turns in the technical disciplines and around 165 turns in the speed events (Gilgien et al., 2018) where the ground reaction force (GRF) and intensity vary during each turn (Supej et al., 2015).

During a skiing descent (described as a run henceforth) both aerobic and anaerobic processes are active and earlier studies have showed that around 65% of the energy comes from anaerobic processes (Turnbull et al., 2009). Although previous research has found associations between aerobic power and ski performance (Neumayr et al., 2003), more recent studies have suggested that there is no correlation (Koller & Schobersberger, 2019; Nilsson et al., 2018; Schobersberger et al., 2021). Nor has strength been shown to have any correlation with performance (Maffiuletti et al., 2006; Neumayr et al., 2003; Nilsson et al., 2021) but strength is still seen as an important capacity for success in alpine skiing due to the high forces that act on the skier during a run (Ferguson, 2010; Neumayr et al., 2003).
1.1 Background

1.1.1 The annual plan

Even if it seems that no single physical capacity correlates with ski performance, elite skiers put a lot of work in their physical training since all of the capacities are important. During the off season they train all the capacities (i.e aerobic, anaerobic, strength, power, coordination, balance and mobility) to prepare for the ski season (Gilgien et al., 2018). The planning of the overall training, which consists of both skiing, strength and conditioning, is a difficult task for the coaches because of the mix of all physical capacities that are needed for development (Gilgien et al., 2018; Hydren et al., 2013). The off-season for alpine elite skiers is relatively long and lasts between May to July due to the northern hemisphere (Gilgien et al., 2018; Hydren et al., 2013) and during this period the strength and conditioning training is the main focus (Hydren et al., 2013). The on-snow preparation beings in the end of August, where the skiers still work to develop, but mostly maintain, their strength and aerobic fitness (Gilgien et al., 2018).

In the end of the preparation period it is normal that the training shifts towards a more sport specific approach (Issurin, 2010) and since alpine skiers start to ski during this period the overall training will automatically become more sport specific (Gilgien et al., 2018). When the competitive premiere approaches and during the competition period the strength and
conditioning focus shifts completely to maintaining the capacities (Gilgien et al., 2018). Even though the volume of strength and conditioning training is remarkably reduced during the ski season, earlier studies have shown higher values in both VO2\text{max}, squat jump (SJ) and counter movement jump (CMJ) after the competition season in comparison with the physical values before the ski season started (Gross et al., 2009). This indicates that alpine competitive skiing can strain the body enough during the season for physical capacities to continue to develop. However, since the off-snow season is long, skiers and coaches do search for new ways to develop the sport specific strength during the off-season.

1.1.2 Kinetics and Kinematics in Alpine Skiing

The ski turn is, as mentioned above, normally divided into four phases. During the turn, elite skiers are subjected to ground reaction forces (GRF) between 2-5 times their own bodyweight (BW) in all disciplines (Gilgien et al., 2020; Gilgien et al., 2014; Supej et al., 2020). Gilgien et al. (2020) also showed that a steeper terrain led to a higher GRF so a shifting terrain may set higher demands on the skier. Earlier research has found the same pattern but also that the highest GRF occurs in the second part of the steering phase no matter if the terrain was steep or flat (Falda-Buscaiio et al., 2017; Supej et al., 2015) and it seems that less GRF after passing the gate is beneficial for performance due to the natural laws of physics. In general, a higher GRF generates a higher energy dissipation (Supej et al., 2011) and since a higher energy dissipation is related to a lower performance (Supej & Holmberg, 2019) the high GRF may not be desireable. Regardless, high GRF will occur during a run and according to Ferguson (2010) the forces primarily occur during isometric and eccentric muscle actions.

Studies that have measured muscular contractions during a ski turn have described eccentric, isometric and concentric phases (Berg et al, 1995: Berg & Eiken, 1999: Alhammoud et al., 2020: Kröll et al., 2015). According to older studies, the eccentric phase during a ski turn is dominant over the concentric (Berg et al., 1995) and electromyography (EMG) data have also shown a high co-activation in the quadriceps and hamstring demonstrating that isometric muscle actions occur (Hintermeister et al., 1995). Berg & Eiken (1999) strengthened the evidence that SL, GS and SG are dominated by eccentric muscle actions in studies on alpine elite skiers from the Swedish national team during the 1990’s. However, the ski equipment has undergone considerable changes during the last decades and after the winter Olympics in 1998 the ski radius got shorter which also changed the skiing technique dramatically (Supej & Holmberg, 2019).
More recent studies have provided evidence that the eccentric phase may not be as dominant as indicated in earlier studies. It seems that the highest GRF occur during the isometric or “quasi-isometric” phase where the knee angle is relatively constant (Kröll et al., 2015). The quasi-isometric contraction is defined as attempting to hold an isometric position but shifts between small concentric and eccentric contractions until failure (Oranchuk et al., 2019) and because of the high GRF in skiing, the desired isometric contraction cannot necessarily be maintained. In this study the quasi-isometric contraction is included in the concept of an isometric contraction. Alhammoud et al. (2020) showed that the isometric phase in GS has a relative time cycle of 34% during the turn. It seems that the isometric phase has a longer relative duration in the speed disciplines than in the tech disciplines and the concentric phase seems to be dominant in SL (Alhammoud et al., 2020). The outside knee during a ski turn starts with a concentric phase (extension), followed by a quasi-isometric phase, and ends with an eccentric phase (flexion). The eccentric phase has a relatively low GRF, in relation to the isometric phase, because the eccentric phase occurs in the completion phase (Kröll et al., 2015). The kinematics are confirmed by Alhammoud et al. (2020) who found similar patterns in all disciplines. In conclusion, the eccentric phase may not be as dominant as studies showed during the 1990’s presumably partly due to the developments in technique and equipment.

The knee angles during a turn vary between a maximum value from 140° in the outside leg and a minimum of approximate 90° (180° = fully extended leg), sometimes even lower, in the inside leg (Kröll et al., 2015). When investigating the angular velocities in alpine skiing, early studies during the 1990’s showed slow angular velocities of 30-80°/s (Berg et al., 1995) and recent studies has shown mean knee angular velocities between 45-90°/s (Alhammoud et al., 2020).

Despite the relatively slow angular velocities, alpine skiing is seen as an explosive sport where the skiers need to rapidly contract the muscles during the turn (Kröll et al., 2015; Turnbull et al., 2009). Since the muscle actions vary during a turn (Alhammoud, et al., 2020; Berg et al., 1995; Tesch, 1995; Kröll et al., 2015) the ability to coactivate and shift muscle activation may be important for ski performance. According to Flanagan and Comyns (2008) the reactive strength is defined as the ability to create as much force as possible when making a fast shift from an eccentric to a concentric movement. The ability to produce force fast
when switching contraction type, may help the skier to maintain an isometric phase without failure during the turn. The ability to shift from an eccentric to an concentric movement may be beneficial if the stretch shortening cycle (SSC) is involved where the muscle lengthens during the eccentric phase, is followed by a rapid transition to a concentric phase where the muscle shortens. (Nicol et al., 2006). However, there is very little knowledge about the importance of SSC in alpine elite skiing since no previous research have been done in this area.

### 1.1.3 Alpine skiing & strength profiling

When testing alpine elite skiers, it is common to divide the physical profiling into different capacities (i.e. strength, aerobic and anaerobic etc.) where each capacity has its own value (Ferland & Comtois, 2018). Since there is a lack of knowledge concerning which specific capacity best correlates with ski performance (Nilsson et al., 2021), future studies should look further into the specific capacities that might be vital for performance (i.e. strength in the lower limb) (Neumayr et al., 2003). Strength is a broad capacity and is usually divided into maximal, power, endurance, and reactive strength where all sub-capacities are tested by different methods to evaluate the strength of an athlete (McGuigan et al., 2013). Maximal strength tests evaluate the peak force that can be created during concentric, eccentric and isometric actions and jump tests such as squat jump (SJ), counter movement jump (CMJ) and drop jump (DJ) can be used to increase power and reactive strength (McGuigan et al., 2013). These strength qualities might be important parameters when evaluating alpine elite skiers and their strength profile because of the characterization of the specific sport. Few studies have analyzed the specific strength profile of alpine skiers and previous work has focused on either 1 repetition maximum barbell back squats or SJ and CMJ as individual results (Nilsson et al., 2018; Nilsson et al., 2021). In a relatively new study, Alhammoud et al. (2019) investigated the differences in eccentric and concentric strength between sex and discipline (i.e. technical or speed) in alpine elite skiing using an open chain isokinetic dynamometer. They did not find any differences in the strength profile between either sex or discipline but since they did not use a control group the results cannot explain if these results are specific for alpine elite skiers or if this is common in other populations or for other athletes.
1.1.4 Concentric, Eccentric, Isometric and Power Strength

According to the force-velocity relationship (see figure 2) a muscle can create higher force in eccentric contractions in relation to the isometric and the concentric contractions. Further, during concentric contractions, the higher the velocity, the less force can be created by the muscle (Tinwala et al., 2017). Most of the strength tests that are used for testing alpine elite skiers (i.e. SJ, CMJ and barbell back squats) are limited by the concentric contraction and since alpine skiing is characterized by all contraction types (Alhammoud et al., 2020), testing eccentric and isometric strength would also appear to be important. By testing the ability to create force in both eccentric and isometric muscle actions, strength and conditioning coaches can form the annual plan to train more specific strength capacities if necessary.

*Figure 2 – Traditional force-velocity relationship curve regarding eccentric, isometric and concentric muscle actions (Giakoumis, 2020).*

Eccentric training is a method that has been proven to evaluate maximal strength, power and alpine ski performance while it simultaneously may assist in preventing injuries (Vogt & Hoppeler, 2014). Eccentric overload training has shown to be more effective than classic free weight training to improve both concentric and eccentric strength, power strength and muscle hypertrophy (Maroto-Izquierdo et al., 2017). Some studies have also found improvement in the SSC from eccentric exercise due muscle tendon adptions (Douglas et al., 2017). There is also some evidence that progressive eccentric exercise can prevent delayed onset muscle soreness (Hody et al., 2019). However, it seems that eccentric training primarily improves the
eccentric strength and concentric strength primarily improves the concentric strength (Higbie et al., 1996) which indicates that specific training may be required to optimize each capacity.

Isometric strength also has a strong correlation to performance in explosive and dynamic strength that involved high forces (Juneja et al., 2010). It seems that isometric training may be beneficial to improve both isometric strength and jump performance in SJ but not in CMJ which may be an indicator that isometric strength does not improve movements that involve the SSC (Lum & Barbosa, 2019). Lum & Barbosa (2019) recommend that isometric strength training may be beneficial to improve sport specific movements in spots where isometric actions occur. Therefore, isometric training might be beneficial for alpine skiers. Since SJ and CMJ are tests that are used frequently when testing alpine elite skiers and since eccentric strength exercise may improve the SSC (Douglas et al., 2017) the eccentric utilization ratio (EUR) may be used as a method to evaluate athletes’ SSC performance (Kipp et al., 2021). The EUR is calculated by dividing the CMJ jump height by the SJ jump height. This results indicates an athlete’s ability to use the SSC (Kipp et al., 2021). Furthermore, the reactive strength may be important and tested to evaluate the athlete’s ability to shift from the eccentric muscle action to a concentric action which provides an indication of the explosive capability (Flanagan et al., 2008).

In summary, recent studies have shown that alpine elite skiing has changed since the 1990’s and the muscle work during the specific events appears to be less eccentric than before. The amount of skiing and the high forces that act on the skier during the snow season may have an impact on the development of isometric, eccentric, concentric, power and reactive strength. The specific strength for alpine skiing may increase during the snow season but since earlier research has not examined how an alpine strength profile differs from other highly trained strength athletes, this hypothesis remains unclear. Therefore, it is unclear what type of strength that categorizes alpine elite skiers and what sport specific strength in alpine elite skiing is.

1.2 Purpose and Research Questions

By looking at an alpine annual cycle, it would appear that the total load of skiing should give the skiers a considerable volume of strength training while skiing. The purpose of this study is to create an alpine strength profile for alpine elite skiers and compare this to other well trained
strength athletes. By investigating whether concentric, eccentric, isometric, power and reaction strength differ between the groups we can investigate what characterizes leg strength in alpine elite skiers. Further, the results can also be used to discuss which type and velocity of contractions should be developed for alpine sport specific strength training or whether all capacities should be used as elements in the basic preparation training to develop general strength and power. The study also aims to determine whether the eccentric and isometric strength correlate with the RSI and the SSC.

1.2.1 Research Questions

1: Does the strength profile differ between alpine elite skiers compared to other well trained strength athletes?

2: Does the isometric strength at different knee angles differ between alpine elite skiers and other well trained strength athletes?

3: Does the eccentric and isometric strength correlate with the jump profile (SJ, CMJ, DJ, RSI and the SSC) among all participants and alpine skiers alone?

2 Method

2.1 Study Design

The investigation was performed between February and May in 2022 in the Biomechanics and Motor Control Laboratory (BMC) at The Swedish School of Sport and Health Sciences (GIH) in Stockholm, Sweden. The thesis had a quantitative approach with a cross-sectional study design where alpine elite skiers were compared with other well trained strength athletes. The participants were encouraged not to change their normal behavior before or between the test sessions but were asked to avoid lower limb strength training the day before and between the test occasions.

2.2 Subjects

To analyze the strength profile for alpine elite skiers one group of alpine elite skiers (SKI) and a control group were used. The SKI group consisted of 11 alpine elite skiers, six men and five
women (mean ± SD, age: 21.3 ± 1.9, height: 176.8 ± 9.1, weight: 77.1 ± 15.1), who were a part of either the Swedish national team or the Swedish alpine university team. The control group consisted of 13 well trained strength athletes, 10 men and three women (mean ± SD, age: 25.8 ± 4.1, height: 178.6 ± 7.2, weight: 85.6 ± 15.8). The control group had at least two years of experience in heavy resistant strength training and trained lower limb strength at least three times per week. To ensure that all participants (SKI and control) had relevant strength, men were required to lift at least 1.5 times and women 1.3 times their own BW in a deep barbell back squat without any assistance.

The SKI participants were recruited from the Ski Team Sweden university and national teams. The participants for the control group were primarily recruited from the Riksidrottsuniversitetet (RIU) in Sweden and among students from GIH that fulfilled the inclusion criteria. All the athletes that were included in the study had an ongoing or a former career within sports.

2.3 Procedure

The participants attended a total of two test occasions at GIH. At the first occasion, the participants performed the jump tests on the force plates as well as a familiarization test in the isokinetic dynamometer (IsoMed 2000, D&R Ferstl GmbH, Hemau, Germany) for the upcoming strength test. The second occasion consisted of the strength test in the IsoMed 2000. Between occasions the participants rested for a minimum of 48 hours and every test began with a 10-minute warm-up on a bicycle ergometer (Monark 829, Monark Exercise, Varberg, Sweden) with an intensity of 1.5W/kg BW and a cadence of approximate 70RPM according to the procedure described by Dirnberger et al. (2013).

2.3.1 The Jump Tests

Two force plates (Kistler 9281EA, Kistler AG, Winterthur, Switzerland) were used to measure the GRF during the jump tests. The sampling frequency was set at 2400 Hz and the data were collected in Qualisys Track Manager (QTM; Qualisys AB, Gothenburg, Sweden) for further analysis.

The jump tests consisted of SJ, CMJ and DJ. Each test consisted of three trials with 60 s rest between each trial. The participants were instructed to jump as high as possible with the hands
placed on the hips during each trial. For the SJ the participant stepped on to the force plates and squatted down to an approximate 90° knee angle to hold that position. The test leader started the countdown from 3 (3, 2, 1, jump). At the jump signal the participant jumped, without lowering the center of the mass in the take-off phase, as high as possible and landed again with both feet on the force plates. For the CMJ the participant stepped on to the force plates and after standing still for three seconds the test leader gave the instruction to start the jump. The participant squatted down to an approximate 90° knee angle. At 90° the participant immediately shifted from the eccentric movement to a concentric movement trying to jump vertically as high as possible.

For the DJ the participant was instructed to jump down from a box with a height of 30 cm, landing with one foot on each force plate. When landing the participant squatted down to an approximately 90° knee angle and then reversed the movement and jumped vertically as high as possible landed back on the force plates with a double jump. The participant was instructed to jump as high and fast as possible during the DJ where the goal was to reach a squat depth of approximately 90° knee angle.

After the jump tests the participants rested for 10 minutes before they performed the closed chain familiarisation test in the IsoMed 2000. The familiarisation test was performed according to the recommendations by Dirnberger et al. (2013). The familiarisation test included three isometric trials in three different positions and three sets of five repetitions at three different concentric and eccentric velocities.

2.3.2 The Strength Test

For the strength test the IsoMed 2000 (D&R Ferstl GmbH, Hemau, Germany) was used with the leg press adapter (E750-560) for measuring the closed chain lower limb strength. The sampling frequency was set at 2500 Hz and the data were collected in QTM for further analysis.

The participant was seated in the IsoMed 2000 with the feet placed on the force plates on the attached leg press. The participants were barefoot during the test. The hip angle was set to 75° (0° = full extension) and the ankle was set to an angle of 15° plantar flexion. The feet were placed at shoulder width with one foot on each force plate. Tape was used to mark the
placement of the feet for standardized position at each set and repetition. For a fixed seated position shoulder adapters were used similar to the setup used by Dirnberger et al. (2013). The range of motion (ROM) for the knee was set to approximately 20°-100° (0° = full extended) using a goniometer. To avoid the risk of hyperextended knees during the trials the most extended position was customised to exclude this risk. The most extended knee angle varied between 20°-30° because of the padded seat. Stronger athletes pressed themselves into the seat which resulted in slightly more extended legs.

The isometric test was performed in 10 different positions within the set ROM. One single repetition of five seconds maximal voluntary isometric contraction (MVIC) was performed at each position with a 90 s rest between sets. After the 10 isometric trials the participant stood up and rested for two minutes before the isokinetic concentric test started. The different isokinetic velocities for the concentric tests were set to three repetitions at 50 mm/s, five repetitions at 100 mm/s and five repetitions at 300 mm/s. The rest between each set was set to 90 s and between each repetition the velocity back to start position was set to 50 mm/s for a standardized rest between repetitions. After the concentric test the participant stood up and rested for another two minutes before the eccentric test started.

The eccentric test consisted of three repetitions at 50 mm/s, five repetitions at 100 mm/s and five repetitions at 300 mm/s with a rest of 90 s between the sets and a velocity back to start position set to 50 mm/s for a standardized rest between repetitions. To activate each eccentric repetition the participant had to press 1000 N before the force plates started to move towards them. This design was chosen to achieve a standardized pre activation and before each repetition.

### 2.4 Measuring Instruments and Data Processing

#### 2.4.1 Kistler Force Plates

For the jump tests two force plates (Kistler 9281EA, AG Winterthur, Switzerland) with dimensions of 600 mm x 400 mm were used. Both force plates were mounted and submerged in the floor at the BMC at GIH. The force plates registered any force acting on the plates which was used to identify and analyze the different jumps. The force plates identified vertical forces (Fz), medial-lateral forces (Fy) and anterior-posterior forces (Fx). For this thesis only the Fz force was analyzed.
2.4.2 IsoMed 2000-system

For the strength test the IsoMed 2000-system (D&R Ferstl GmbH, Hemau, Germany) was used. The IsoMed 2000 consists of an adjustable seat, a screen with a visual biofeedback and a rotational dynamometer that was adapted by the leg press device to enable linear movements. The dynamometer could be mounted to two different gears depending on required linear velocities. Gear I reach velocities up to 800 mm/s and forces up to 9000 N and gear II reaches velocities up to 1200 mm/s and forces up to 6000 N. For this thesis gear I was chosen due to relatively slow velocities and given that high forces were expected.

2.4.3 Qualisys Track Manager

Qualisys Track Manager (QTM; Qualisys AB, Gothenburg, Sweden) was used to collect the data from both the jump and the strength tests. For the jump tests the GRF was collected from the Kistler force plates. The data collection for the strength tests were collected as Volt, from the integrated IsoMed 2000 computer. The Volt signals represented both the positioning of the force plates on the leg press and the force that the participant exerted on each force plate. The sum of both force plates and the positioning data were collected in QTM for further analysis.

2.5 Validity and Reliability

To maintain a high standardisation during the experiments a standardised protocol was used, and all the participants received the same instructions before, during and after the tests. The protocol for the strength test was especially evaluated due to the differences in the participants’ anthropometrical characteristics (Dvir and Müller, 2019). The same test leaders monitored all test sessions and since the participants performed a familiarization session, they were aware of what to expect during the data collection, thus increasing the internal validity. Further, earlier reproducibility studies found significant changes (p = 0.05) from the first to the second trial when measuring concentric and eccentric strength (Dirnberger et al., 2013) and the single joint concentric (Dirnberger. 2012b) and eccentric (Dirnberger et al., 2012a) strength. Therefore, a familiarisation test was necessary for a higher validity.

Isokinetic dynamometry is seen as the gold standard for measuring strength (Dirnberger et al., 2013) and the IsoMed 2000 has shown moderate to high reproducibility (Dirnberger et al.,
The IsoMed 2000 has a strong reproducibility for strength with an intraclass correlation coefficient (ICC) for concentric (ICC=0.937-0.978) and eccentric (ICC=0.823-0.951) strength (Dirnberger et al., 2013). For isometric measurements The IsoMed 2000 has a strong reliability in repeated measurements in single joint tests (ICC=0.924-0.969) (Dirnberger et al., 2012b) which should indicate a high overall reliability in the IsoMed 2000 tests performed in this study.

Force plates have long been seen as the gold standard method for measuring GRF and the Kistler (9281EA) is frequently used to evaluate other devices (Blosch et al., 2019). The RSI has shown a high reliability (ECC=0.989) when used for the 30 cm depth jump test (Flanagan et al., 2008).

2.6 Ethics

The participant received written and oral information about the procedure which includes potential risks that can occur during and after the test. To ensure that the participant was aware of the purpose of the study and that they had the choice to cancel their participation whenever they want, they signed a consent form before the study began. The study was approved by the Swedish Regional Board of Ethics (Dnr: 2021-06808-01). All participants were assigned a code, which was available only to the researcher performing the study and the researcher responsible for the study. The reported data cannot be linked to a specific individual. The data were stored locally on a password protected computer and back-up was saved on external hard drives. The raw data will be stored at GIH’s remote desk at GIH.

2.6 Data- and Statistical Analysis

2.6.1 Data Analysis

All raw data from the force plates and the Isomed 2000 were collected, controlled and exported to C3D-files in QTM for further analysis in Visual 3D (C-Motion Inc, Germantown, USA, v. 2021.02.01). All data were filtered with a Butterworth lowpass filter with a cutoff frequency at 50 Hz.
To analyze the jump heights the GRF of the two separated force plates was added to one signal and specific events were identified in Visual 3D to calculate the jump heights (see figure 3).

**Figure 3 - Description of jump analysis.** Identified events that were used to analyze jump heights with either the time in air or take-off velocity method. (TIA=Time In Air).

The quiet stance is the phase before the jump where the participant stood as still as possible. During this event the weight of the participant was identified by calculating the mean value of the GRF during 1 second. The mass of the participant was further calculated by dividing the weight by the gravitational constant (9.81). The start of the jump was identified when the GRF decreased with 50 N for the CMJ or increased by 50 N for the SJ from the normative weight value that was calculated during the quiet stance. This event was set as the start of the impulse and the impulse ended when the participant left the force plates at take-off. The impulse is defined as the sum of all forces under the curve between the start of the jump and the take-off. The event “landing” shows when the participant landed back on the force plates after the jump. The time between the take-off and landing was used to calculate the jump height using the time in air (TIA) method.

For the SJ and CMJ test the jump heights were calculated using the take-off velocity (TOV) method due to the use of force plates and recommendation from Moir (2008).

\[
\text{TOV} = \frac{F \times t}{m}
\]

\[
\text{TOV jump height} = \frac{\text{TOV}^2}{2g}
\]

The height of the DJ was calculated with the TIA method since the TOV is not suitable for DJ. The TIA method was also used for the SJ and the CMJ to verify the jump heights but is not included in the results. For the DJ the RSI was also calculated. The RSI was calculated by
dividing the jump height during the DJ by the ground contact time (Flanagan & Comyns, 2008). The ratio between the CMJ and the SJ was used to identify the EUR.

$$TIA = \frac{1}{2} g \left( \frac{t}{2} \right)^2 - v_0$$

$$RSI = \frac{\text{Jump height (cm)}}{\text{Ground contact time (s)}}$$

$$EUR = \frac{\text{CMJ jump height}}{\text{SJ jump height}}$$

The highest jump and the highest RSI value of the three trials in respective jump was noted as the result for each jump. Only the highest CMJ and SJ jump were used to calculate the EUR.

The data from the strength test was converted from voltage to Newton (N) and position (mm). To calculate the force data the sum of both the left and the right force plates on the force platform were added as one signal. After force and position were determined the peak force within every repetition was identified and the highest peak within each set was noted as the result. For the isometric sets the peak force was required to appear within the five seconds of each set and when the position of the force platform was set to the specific position. After the five seconds contraction the force platform moved to a neutral position during the rest period and if the participant continued to press a higher value could be displayed. If this occurred, the highest value at the specific position was used (see figure 4).

![Diagram](image-url)

**Figure 4** – Description of isometric peak analysis. The peak force during the isometric test was identified between the start of the set (Start Set) and the end of the set (End Set).
During the concentric and the eccentric tests, the peak force during each set was required to appear during the relevant repetition. The relevant repetition of the concentric test was determined as when the force plates moved away from the participant. The relevant repetition for the eccentric tests was instead determined as when the force plates moved towards the participant. In some cases, the peak force occurred when the force plates shifted trajectory. (Ie. when the force plates shifted from a movement away from the participant to a movement towards the participant and vice versa). When this occurred, the forces were outside the relevant repetition and were therefore excluded from the results. Only the peak value for each respective set was counted as the test result (see figure 5).

![Figure 5 – Description of concentric and eccentric peak analysis. Events and description of the analysis of the isokinetic strength test. As an example, the Peak value in repetition 2 was not accepted.](image)

### 2.6.1 Statistical Analysis

The statistically analyse was performed in IBM SPSS Statistics Subscription (v.28.0.1.1). Descriptive statistics were presented for each variable (mean ± SD) and the Shapiro-Wilks test was used to check if the data were parametric due to the small sample size (n<50). To examine the strength profile and the differences between the groups an independent T-test was used since the data were parametric. To examine the correlations between the eccentric and isometric strength with the DJ, SSC and RSI the Pearson’s product moment correlation coefficient was performed due to the parametric data. To define the relationship the categories
small \((r=0.10 - 0.29)\), moderate \((r=0.30 - 0.49)\), large \((r=0.50 - 0.69)\), very large \((r=0.70 - 0.89)\), nearly perfect \((r=0.90 - 0.99)\), and perfect \((r=1.0)\) was used according to Hopkins (2000). The significance level was set to \(P \leq 0.05\) for all tests.

### 3 Results

A total amount of 24 participants performed the tests where the ski group consisted of 11 alpine elite skiers (five women and six men) and 13 strength trained athletes (three women and 10 men).

**Table 1 - Anthropometry descriptive values for the participants in each group \((N=number\ of\ participants,\ SD=standard\ deviation)\).**

<table>
<thead>
<tr>
<th>Variables</th>
<th>SKI (N=11)</th>
<th>(\text{mean} \pm SD)</th>
<th>CONTROLL (N=13)</th>
<th>(\text{mean} \pm SD)</th>
<th>All Participants (N=24)</th>
<th>(\text{mean} \pm SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (cm)</td>
<td>176.8 ± 9.1</td>
<td>178.6 ± 7.2</td>
<td>177.7 ± 8.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77.1 ± 15.1</td>
<td>85.6 ± 15.8</td>
<td>81.7 ± 15.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>21.3 ± 1.9</td>
<td>25.8 ± 4.1</td>
<td>23.7 ± 3.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**3.1 Strength and Jump Profile**

The jump test showed significantly higher relative values, in relation to BW, for the ski group compared to the control group \((P < 0.05)\) and also a significantly higher RSI for the ski group \((P \leq 0.05)\). The SKI group performed higher absolute values in SJ, CMJ, DJ and RSI but no significant differences were observed (see figure 2).

**Table 2 – The jump profile. Absolute and relative values for the jump tests \((N=number\ of\ participants, SD=standard\ deviation, SJ=squat\ jumps, CMJ=counter\ movement\ jumps, DJ=depth\ jump, RSI=reaction\ strength\ index, SSC=stretch\ shortening\ cycle, \*=P-value<0.05, \**=P-value<0.01). P-value is not corrected.**

<table>
<thead>
<tr>
<th>Variables</th>
<th>SKI (N=11)</th>
<th>(\text{mean} \pm SD)</th>
<th>CONTROLL (N=13)</th>
<th>(\text{mean} \pm SD)</th>
<th>(P)-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJ (cm)</td>
<td>36.27 ± 5.14</td>
<td>33.70 ± 6.47</td>
<td>0.299</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SJ (cm/kg)</td>
<td>0.479 ± 0.068</td>
<td>0.398 ± 0.069</td>
<td>0.009**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMJ (cm)</td>
<td>38.46 ± 5.38</td>
<td>35.82 ± 7.05</td>
<td>0.320</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMJ (cm/kg)</td>
<td>0.508 ± 0.076</td>
<td>0.423 ± 0.076</td>
<td>0.011*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DJ (cm)</td>
<td>36.84 ± 5.15</td>
<td>33.36 ± 6.20</td>
<td>0.153</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DJ (cm/kg)</td>
<td>0.488 ± 0.078</td>
<td>0.395 ± 0.069</td>
<td>0.006**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSI</td>
<td>0.84 ± 0.17</td>
<td>0.67 ± 0.19</td>
<td>0.036*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSC</td>
<td>1.0613 ± 0.042</td>
<td>1.0622 ± 0.0618</td>
<td>0.969</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The strength test showed significantly higher relative values, in relation to BW, for the SKI group in the lowest concentric velocity, the isometric and the eccentric tests (P < 0.05). For the absolute strength values, no significant differences were observed but the SKI group performed higher absolute values in all tests, except for the tests with the highest concentric velocities. The most significant difference was observed in the relative isometric value (P < 0.01). (see table 3).

Table 3 – The strength test. Absolute and relative strength values. Number in the variables indicates the velocity (mm/s) during the strength test. (N=number of participants, SD=standard deviation, CON=concentric muscle contraction, ISO=isometric muscle contraction, ECC=eccentric muscle contraction, *=P-value<0.05, **=P-value<0.01). P-value is not corrected.

<table>
<thead>
<tr>
<th>Variables</th>
<th>SKI</th>
<th>CONTROLL</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>mean</td>
<td>±SD</td>
</tr>
<tr>
<td><strong>Strength Profile</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CON300 (N)</td>
<td>11</td>
<td>3192.48</td>
<td>±670.47</td>
</tr>
<tr>
<td>CON300 (N/kg)</td>
<td>41.36</td>
<td>±3.28</td>
<td>38.97</td>
</tr>
<tr>
<td>CON100 (N)</td>
<td>3740.59</td>
<td>±819.97</td>
<td>3767.54</td>
</tr>
<tr>
<td>CON100 (N/kg)</td>
<td>48.43</td>
<td>±3.37</td>
<td>44.08</td>
</tr>
<tr>
<td>CON50 (N)</td>
<td>3875.39</td>
<td>±856.82</td>
<td>3634.98</td>
</tr>
<tr>
<td>CON50 (N/kg)</td>
<td>50.29</td>
<td>±5.47</td>
<td>42.35</td>
</tr>
<tr>
<td>ISO (N)</td>
<td>6764.15</td>
<td>2172.35</td>
<td>5621.69</td>
</tr>
<tr>
<td>ISO (N/kg)</td>
<td>86.47</td>
<td>±4.77</td>
<td>65.09</td>
</tr>
<tr>
<td>ECC50 (N)</td>
<td>4845.06</td>
<td>±1448.62</td>
<td>4129.83</td>
</tr>
<tr>
<td>ECC50 (N/kg)</td>
<td>62.54</td>
<td>±11.80</td>
<td>48.90</td>
</tr>
<tr>
<td>ECC100 (N)</td>
<td>4268.13</td>
<td>±981.55</td>
<td>3890.59</td>
</tr>
<tr>
<td>ECC100 (N/kg)</td>
<td>55.51</td>
<td>±8.53</td>
<td>46.13</td>
</tr>
<tr>
<td>ECC300 (N)</td>
<td>3773.39</td>
<td>±861.28</td>
<td>3554.94</td>
</tr>
<tr>
<td>ECC300 (N/kg)</td>
<td>49.28</td>
<td>±8.62</td>
<td>41.99</td>
</tr>
</tbody>
</table>

Table 4 shows the relative strength analysis due to the percentage difference from the isometric strength where the control group showed significantly higher values in the two highest concentric velocities (P < 0.05).
Table 4 – The force-velocity profile. Strength difference in relation to isometric muscle contraction between the groups. Number in the variables indicates the velocity (mm/s) during the strength test. \( N = \) number of participants, \( SD = \) standard deviation, \( CON = \) concentric muscle contraction, \( ISO = \) isometric muscle contraction, \( ECC = \) eccentric muscle contraction, \( *= P\text{-value}<0.05 \). \( P\text{-value} \) is not corrected.

<table>
<thead>
<tr>
<th>Variables</th>
<th>SKI</th>
<th>CON</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>mean ±SD</td>
<td>mean ±SD</td>
<td></td>
</tr>
<tr>
<td>CON300 (%)</td>
<td>11</td>
<td>49.09 ±8.81</td>
<td>61.23 ±13.32</td>
</tr>
<tr>
<td>CON100 (%)</td>
<td>13</td>
<td>57.55 ±9.41</td>
<td>69.23 ±11.99</td>
</tr>
<tr>
<td>CON50 (%)</td>
<td>13</td>
<td>59.36 ±8.78</td>
<td>66.77 ±10.93</td>
</tr>
<tr>
<td>ISO (%)</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>ECC50 (%)</td>
<td>13</td>
<td>73.09 ±11.34</td>
<td>76.77 ±18.74</td>
</tr>
<tr>
<td>ECC100 (%)</td>
<td>13</td>
<td>65.55 ±12.04</td>
<td>73.31 ±18.60</td>
</tr>
<tr>
<td>ECC300 (%)</td>
<td>13</td>
<td>58.46 ±13.25</td>
<td>66.46 ±12.15</td>
</tr>
</tbody>
</table>

Figure 6 – Strength and force-velocity curves. Left figure shows the relative strength development between the groups. Right figure shows the percentage strength difference in relation to isometric muscle contraction between the groups. Numbers on the x-axis indicates the velocity (mm/s) for each test. \( CON = \) concentric muscle contraction, \( ISO = \) isometric muscle contraction, \( ECC = \) eccentric muscle contraction, \( *= P\text{-value}<0.05 \), \( **= P\text{-value}<0.01 \). \( P\text{-value} \) is not corrected.

3.2 Isometric Strength Profile

The isometric strength test showed a significantly higher relative strength for the SKI group between a knee angle between 20° - 60° \( (P < 0.05) \) with the highest significant difference at 25°. The SKI group showed higher values for all knee angles for the isometric strength test where they showed highest relative values at 25° in difference to the control group who showed highest values at 20° (see table 5).
Table 5 – Relative isometric strength profile. (N=number of participant, SD=standard deviation, *=P-value<0,05, **=P-value<0,01). P-value is not corrected.

<table>
<thead>
<tr>
<th>Knee Angle</th>
<th>Variables</th>
<th>SKI</th>
<th>CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>mean ±SD</td>
<td>N</td>
</tr>
<tr>
<td>20° (N/kg)</td>
<td>11</td>
<td>74,32 ±15,34</td>
<td>13</td>
</tr>
<tr>
<td>25° (N/kg)</td>
<td>11</td>
<td>84,22 ±16,31</td>
<td>13</td>
</tr>
<tr>
<td>30° (N/kg)</td>
<td>11</td>
<td>78,87 ±20,73</td>
<td>13</td>
</tr>
<tr>
<td>40° (N/kg)</td>
<td>11</td>
<td>63,59 ±17,63</td>
<td>13</td>
</tr>
<tr>
<td>50° (N/kg)</td>
<td>11</td>
<td>47,74 ±7,85</td>
<td>13</td>
</tr>
<tr>
<td>60° (N/kg)</td>
<td>11</td>
<td>41,03 ±6,53</td>
<td>13</td>
</tr>
<tr>
<td>70° (N/kg)</td>
<td>11</td>
<td>36,24 ±5,94</td>
<td>13</td>
</tr>
<tr>
<td>80° (N/kg)</td>
<td>11</td>
<td>32,28 ±5,42</td>
<td>13</td>
</tr>
<tr>
<td>90° (N/kg)</td>
<td>11</td>
<td>29,42 ±4,69</td>
<td>13</td>
</tr>
<tr>
<td>100° (N/kg)</td>
<td>11</td>
<td>27,42 ±3,91</td>
<td>13</td>
</tr>
</tbody>
</table>

In relation to the values at 20° the SKI group performed significantly higher strength development at 25° which was also significantly higher than the control group (P < 0,05).

There were no significant differences in the strength development at the knee angle between 30°-100° but the SKI group had a higher drop in percent between knee angles 50°-90° (see table 6).

Table 6 – Isometric strength development. Percentage strength difference in relation to the 20° knee angle. (N=number of participants, SD=standard deviation, CON=concentric muscle contraction, ISO=isometric muscle contraction, ECC=eccentric muscle contraction, *=P-value<0,05). P-value is not corrected.

<table>
<thead>
<tr>
<th>Knee Angle</th>
<th>Variables</th>
<th>SKI</th>
<th>CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>mean ±SD</td>
<td>N</td>
</tr>
<tr>
<td>20° (%)</td>
<td>11</td>
<td>100 ±0</td>
<td>13</td>
</tr>
<tr>
<td>25° (%)</td>
<td>11</td>
<td>114,27 ±15,13</td>
<td>13</td>
</tr>
<tr>
<td>30° (%)</td>
<td>11</td>
<td>106,64 ±22,93</td>
<td>13</td>
</tr>
<tr>
<td>40° (%)</td>
<td>11</td>
<td>85,36 ±13,8</td>
<td>13</td>
</tr>
<tr>
<td>50° (%)</td>
<td>11</td>
<td>65,27 ±11,69</td>
<td>13</td>
</tr>
<tr>
<td>60° (%)</td>
<td>11</td>
<td>56,09 ±8,89</td>
<td>13</td>
</tr>
<tr>
<td>70° (%)</td>
<td>11</td>
<td>49,64 ±8,03</td>
<td>13</td>
</tr>
<tr>
<td>80° (%)</td>
<td>11</td>
<td>44,27 ±8,05</td>
<td>13</td>
</tr>
<tr>
<td>90° (%)</td>
<td>11</td>
<td>40,27 ±6,86</td>
<td>13</td>
</tr>
<tr>
<td>100° (%)</td>
<td>11</td>
<td>37,82 ±7,15</td>
<td>13</td>
</tr>
</tbody>
</table>
Figure 7 – Isometric strength curves. Left figure shows the relative strength development for each group. Right figure shows the percentage strength difference between the groups in relation to force production at the 20° knee angle. (*=P-value<0.05, **=P-value<0.01, ***=P-value<0.001). P-value is not corrected.

3.3 Relationships between Strength and Jump variables

For the correlation analysis only small and moderate relationships were found with only one moderate significant correlation for the highest eccentric velocity in relation to the SJ, CMJ and DJ within all participants (see table 7). No significant correlations were observed within the SKI group (see table 8).

Table 7 – Correlation analysis both groups. Results of the correlation analysis between isometric and eccentric strength in relation to the jump profile within all participants. (N=number of participants, ISO=isometric, ECC=eccentric, DJ=depth jump, RSI=reaction strength index, SSC=stretch shortening cycle, *=P-value<0.05). P-value is not corrected.

<table>
<thead>
<tr>
<th>Variables</th>
<th>N</th>
<th>ISO (N/kg)</th>
<th>CMJ (cm/kg)</th>
<th>DJ (cm/kg)</th>
<th>RSI</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>r</td>
<td>P-value</td>
<td>r</td>
<td>P-value</td>
<td>r</td>
</tr>
<tr>
<td>ISO (N/kg)</td>
<td>24</td>
<td>0.239</td>
<td>0.261</td>
<td>0.218</td>
<td>0.305</td>
<td>0.225</td>
</tr>
<tr>
<td>ECC50 (N/kg)</td>
<td>24</td>
<td>0.243</td>
<td>0.253</td>
<td>0.174</td>
<td>0.416</td>
<td>0.181</td>
</tr>
<tr>
<td>ECC100 (N/kg)</td>
<td>24</td>
<td>0.256</td>
<td>0.227</td>
<td>0.215</td>
<td>0.312</td>
<td>0.246</td>
</tr>
<tr>
<td>ECC300 (N/kg)</td>
<td>24</td>
<td>0.426*</td>
<td>0.038</td>
<td>0.381</td>
<td>0.066</td>
<td>0.429*</td>
</tr>
</tbody>
</table>

Table 8 – Correlation analysis SKI group. Results of the correlation analysis between Isometric and eccentric strength in relation to the jump profile within the SKI group. (N=number of participants, ISO=isometric, ECC=eccentric, DJ=depth jump, RSI=reaction strength index, SSC=stretch shortening cycle, *=P-value<0.05). P-value is not corrected.

<table>
<thead>
<tr>
<th>Variables</th>
<th>N</th>
<th>ISO (N/kg)</th>
<th>CMJ (cm/kg)</th>
<th>DJ (cm/kg)</th>
<th>RSI</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>r</td>
<td>P-value</td>
<td>r</td>
<td>P-value</td>
<td>r</td>
</tr>
<tr>
<td>ISO (N/kg)</td>
<td>11</td>
<td>-0.32</td>
<td>0.338</td>
<td>-0.329</td>
<td>0.323</td>
<td>-0.396</td>
</tr>
<tr>
<td>ECC50 (N/kg)</td>
<td>11</td>
<td>-0.101</td>
<td>0.768</td>
<td>-0.15</td>
<td>0.659</td>
<td>-0.25</td>
</tr>
<tr>
<td>ECC100 (N/kg)</td>
<td>11</td>
<td>0.099</td>
<td>0.091</td>
<td>0.082</td>
<td>0.810</td>
<td>0.015</td>
</tr>
<tr>
<td>ECC300 (N/kg)</td>
<td>11</td>
<td>0.079</td>
<td>0.818</td>
<td>0.112</td>
<td>0.744</td>
<td>0.080</td>
</tr>
</tbody>
</table>
4 Discussion

The main aim of this study was to investigate the strength and jump profile within a group of alpine elite skiers. Alpine skiing has changed since the 1990’s and the sport specific movements during the turn might not be as eccentric and isometric as previously described. The concentric strength might be more important today since alpine elite skiing is seen as an explosive sport. The study also investigated the isometric strength profile in detail to see if the strength development differs between the SKI and the control group depending on knee angle since alpine elite skiers primarily work with a relatively straight outside leg during the turn (Alhammoud et al., 2020). Further, the study also aimed to see if the isometric and the eccentric strength correlated with the jump profile (SJ, CMJ, DJ, RSI and SSC) since previous research has shown that eccentric strength training might be beneficial for the development of the SSC (Douglas et al., 2017). Additionally, isometric strength has a strong correlation with performance in explosive sports (Juneja et al., 2010) whereas primarily SJ performance is improved from isometric training (Lum & Barbosa, 2019).

The main findings were that the relative strength in the SKI group was significantly higher in slow concentric isometric and all the eccentric muscle actions compared to the strength trained control group. However, the absolute values did not show any significant differences. The control group showed higher absolute values in the moderate and fast concentric tests while the SKI group showed higher values in the remaining tests. For the isometric specific strength profile, the SKI group showed higher relatively values in all knee angles, significant in the 20°-60° range of motion where the peak strength occurred in different knee angles between the groups. The SKI group increased the strength development by 14,27% (±15,13%) and the control group decreased by 0,47% (±12,43%) from the 20° knee angle to the 25° knee angle (P=0,016). When looking at the correlation between the strength and the jump profile, only small to moderate relationships were found, where only the ECC300 strength was significantly correlated (P=0,05) to the SJ, CMJ and DJ.

4.1 The Strength and Jump Profile

The main findings in the strength profile showed that alpine elite skiers have a greater isometric strength compared to the control group both in absolute and relative values. According to the relative strength results the alpine skiers were stronger in all tests, except for the moderate and fast concentric tests where no significant results were found (P=>0,05).
These results are in line with the movement patterns from previous studies that have shown that the knee angle velocity is relatively slow in both eccentric and concentric movements during a ski turn (Berg et al., 1995; Alhammoud et al., 2020). The control group consisted of well-trained strength athletes with different sports background, where most of the sports included running (e.g., American football, hockey, soccer, sprinters). Earlier studies have shown relatively fast knee angular velocities in sprinting (<1185°/s) and around 300°/s in jumping (Cross et al., 2021) in comparison to alpine skiing, where the velocities vary between 20°-90°/s (Alhammoud et al., 2020; Berg et al., 1995; Tesch, 1995). It is therefore maybe not surprising that the study showed these differences in strength between the groups, since alpine skiers might be more experienced in the slow knee angular velocities.

The result also indicate that the specific muscle action is an important factor while analysing alpine elite skiers’ strength profile. The studies from the 1990’s that found evidence that alpine skiing consisted of slow angular velocities, where isometric and eccentric muscle work was prominent, may still be relevant (Hintermeister et al., 1995; Tesch, 1995; Berg & Eiken, 1999). However, since a higher level of significance was shown for the isometric and the slow concentric strength (P<0.01) this may indicate that isometric and slow concentric muscle work may be more sport specific in modern skiing. Alhammoud et al. (2020) showed that the isometric, concentric and eccentric phases during a turn in GS have similar relative durations and that the highest knee angular velocities occur during eccentric muscle work (around 90°/s). This may explain why alpine skiers are significantly stronger in the fastest eccentric muscle action compared to the control group (P<0.05). The eccentric movement during a ski turn occurs during the unloading phase where the forces are relatively low. However, since the highest forces occur in isometric muscle work, which is followed by the eccentric movement (Kröll et al., 2015), the ability to produce high forces in fast eccentric movements may be important. These results also support the theory by Turnbull et al. (2009), who suggested that the explosiveness in alpine skiing might be explosiveness in eccentric and not concentric muscle actions. Turnbull et al. (2009) also indicated that this eccentric load does not occur in other sports which might explain the significant differences between the groups.

Since the SKI and the control groups had different training histories due to different sports and anthropology, the heterogeneity could have made the results invalid since one group could have been generally stronger in all tests. However, when looking at the absolute values this seems to not be the case. The absolute values did not differ significantly, but the control
group had higher absolute values in the fast and moderate concentric muscle strength (see table 3). In the other isokinetic strength tests the SKI group showed higher absolute values which indicates that the fast concentric movements may not be specific for alpine elite skiers. As mentioned above, the absolute values for the strength test were not significant but shows that there might be a difference in the strength profile between the groups.

Alpine skiing is seen as an explosive sport (Turnbull et al., 2009) and this study strengthens this notion. However, the alpine skiing strength profile shows explosive muscle strength in eccentric movements. Alhammoud et al. (2020) found peak knee angular velocities at 124°/s in SL in the eccentric movement and they believe that the dryland training should be focusing on strength training in slow angular velocities with implements of rapid force development. The results from this study, where the alpine elite skiers were significantly stronger in the fast eccentric muscle action, strengthens this recommendation where the skiers performed better than the control group in the fast eccentric movements. The SKI group had just finished their skiing season while performing the test and their strength may therefore be more sport specific than if they had been training in the gym during the last 6 months.

The SKI group performed significantly better in the jump test while analysing the relative values. However, the absolute values did not show any significant differences. The control group was heavier than the SKI group in general, which could explain these differences in absolute and relative measures. Since no measurement for body composition was used, this is something that could have affected the jump results since we do not know the fat free mass of the participants. Though, even if the absolute results were not significant the SKI group trend to jump higher than the control group.

Previous studies indicated that SJ correlates with lower limb strength (Wisloff et al., 2004) and during a CMJ athletes tend to jump higher due to the SSC (Kipp et al., 2021). Since the SSC may be developed by eccentric training (Douglas et al., 2017) the eccentric muscle actions that occur during alpine skiing might have the same effect. As mentioned above, the results from this study indicate that eccentric strength might be specific for alpine elite skiing but the EUR does not differ significantly between the control and the SKI group. This result suggests that alpine skiing is not eccentric enough to develop SSC since there is no difference in EUR between the groups after an alpine ski season. This area needs further research since we do not know the input values of the SKI group before the ski season began and how the
season has affected the SSC. By calculating the EUR from previous studies (CMJ/SJ=EUR) a study by Gross et al. (2009) showed a similar, slightly decreased EUR value after the alpine ski season. However, according to previous research, the SSC is also developed from fast concentric training which according to this study is not sport specific for alpine skiing. This might therefore be the reason why alpine skiing does not develop the SSC.

Since the SKI group had significantly higher RSI values, the reaction strength might be specific for alpine elite skiing. The duration of an SL turn is approximately 0.87 seconds (Supej et al., 2020) where concentric, isometric and eccentric muscle actions occur with relatively similar durations in the respective muscle action (Alhammoud et al., 2020). That means that an alpine skier needs to shift muscle work fast which can be an explanation why the RSI is significantly higher compared to other well trained strength athletes. However, the results should be interpreted with caution as the RSI is hard to standardize since there is a possibility that the knee angle varies from one participant to another. The longer the duration that a participant has contact with the force plates the lower the RSI and since a deeper squat in the landing results in a longer duration on the force plates the test may have some errors that we need to have in mind.

Another interesting finding was that the force-velocity relationship for eccentric, concentric and isometric muscle actions that Giakoumis (2020) described do not fit into the the strength profile in this study. The previous well established force-velocity curve shows higher force production the lower contraction velocity and even higher force production in eccentric muscle actions in relation to the isometric (Giakoumis 2020). Alhammoud et al. (2019) found evidence when examining the hamstring and the quadriceps muscle separately, that the muscles could create higher torque in eccentric movements than concentric movements. The study by Alhammoud et al. (2019) did not include the isometric contraction and only tested one eccentric velocity. Since the force-velocity curve in this study shows a peak force in the isometric muscle actions for both groups and that higher velocities, no matter if it is concentric or eccentric, reduced the ability to create force. One explanation could be fatigue since the participants started with the isometric test which was followed by the concentric and the eccentric tests. The highest values was shown in the isometric muscle action since the participants may have been more alert in this test. Future studies should therefore randomize the order in which the tests are performed.
4.2 The Isometric Strength Profile

Alpine skiers show significantly higher strength values between 20°-60° knee angle. When looking at the outside knee angle during a ski turn, the angles are between 40°-100° (Kröll et al., 2015). During the isometric strength test it seems that the greatest strength within the SKI group exists at the 25° knee where the highest level of significance appeared (P<001). The SKI group performed significantly better at the 60° knee angle which is the approximate mean knee angle in the technical disciplines (Kröll et al., 2015).

When looking at the GRF data, the peak forces seem to appear when the outside leg is around the most extended position, where isometric actions occur (Kröll et al., 2015; Supej et al., 2020) and that could explain why the skiers showed this significantly greater isometric strength. Another explanation why skiers are stronger in isometric muscle action might be that isometric training is not included in the control group’s training plan. Since the alpine skiers had just finished the ski season one week prior to the test they had been practicing this type of strength during the whole season. According to previous studies, the peak GRF during a turn can reach 2-5 times the skier’s BW (Gilgien et al., 2020; Gilgien et al., 2014; Supej et al., 2020) and since the peak forces appear in isometric muscle actions (Kröll et al., 2015) it is maybe expected that alpine skiers performed better in the isometric strength test immediately after a competitive season.

Interestingly, when looking at the strength curve during the set range of motion, the curves differ between the groups (see figure 7). The percentage change in relation to the 20° knee angle indicates that the SKI group increase the force production at the 25° and 30° before dropping. At the 25° knee angle the alpine skiers differ significantly from the control group and between 50°-100° the ski group produce less force than the control group in relation to the 25° knee angle. This might be new evidence that indicates that isometric strength is important in alpine skiing to handle the high forces during a turn and well-trained strength athletes do not train their peak strength in the extended position as skiers do. During a back squat the hip and the knee extensors muscle effort increases the deeper the squat gets (Bryanton et al., 2012) and the barbell load is therefore adjusted to the deepest position in a back squat. In skiing the peak forces acts on the skier in more extended knee angles which might explain their development in strength between the knee angle at 25°-40° because alpine skiers stress the muscles in this position.
4.3 Isometric and Eccentric Strength vs. The Jump Profile

The correlation analysis only found small and moderate correlations when comparing the eccentric and isometric strength with the jump profile within all participants (N=24). These results are surprising since strength in earlier studies has shown strong correlations to SJ (Wisløff et al., 2004). Since only the fast eccentric strength test had significant (P<0.05) but only moderate correlation with SJ, CMJ and DJ, this study does not support the study by Wisløff et al. (2004). However, on the other hand, Wisløff used a barbell back squat where concentric muscle strength might correlate with the SJ and eccentric strength might not, according to the results in this study. Eccentric strength training has been shown to increase the use of the SSC (Douglas et al., 2017) but according to these results eccentric strength does not relate with the EUR value. Additionally, since eccentric strength training primarily develops eccentric strength (Higbie et al., 1996) this area needs to be investigated further.

No correlation was found when looking at the SKI group alone. This indicates that skiing might not be as eccentric as necessary for the adaptation of the SSC. However, when looking at the strength profile, the isometric and slow concentric muscle movements might be more specific for alpine elite skiers. Since isometric strength training might increase the SJ performance (Lum & Barbosa, 2019) this can counteract the EUR result since the SJ might be more affected by the skiing season than the CMJ. This has also been seen in previous studies where the competitive season developed the SJ to a greater, but not significant, extent than the CMJ (Gross et al., 2009). Since the SSC also improves by fast concentric movements this could be another explanation why EUR did not correlate with the eccentric strength in the SKI group since skiing may be more beneficial for the slow angular velocities and isometric and eccentric strength.

4.4 Limitations

There are two major limitations in this study that needs attention. The first issue occurred during the strength test in the IsoMed 2000 with the leg press adapter. Taller participants had the power plates farther away than shorter participants. This led to that each repetition in the concentric and eccentric tests had a longer duration, since the different velocities is set to mm/second and not knee angular velocities. This may have led to fore fatigue in taller participants. Another standardization issue is that when the participant started the set they pressed themselves into the seat which affected the knee angle. This might have given a small error.
since the most extended position was set when the participant did the warmup press before the isometric test started. In other words, when the participant pressed the warmup set the test leader measured the knee angle with a goniometer where the most extended position was set at approximate 20 ° in the knee joint.

Another limitation with the study was the heterogeneity within the control group. There were large differences in anthropometry between the participants and since the fat free mass was unknown this could have affected the relative results due to BW. In the future, it is recommended that measurements of body composition are included in the inclusion criteria, to resemble the group that is primarily being examined.

4.5 Future research

The main aim of this study was to examine what sport specific strength is in alpine elite skiing. Since the test was performed after the international competitive skiing season, the skiers had presumably adapted to the sport specific requirements of skiing. There is a chance that the strength might have been affected by the ski season since the skiers have been focusing on skiing for the last eight months (Gilgien et al., 2018). In order to see how the ski period actually is affecting the athletes, the same tests should be performed before and after the ski season. This would be interesting because if the dryland training creates another strength profile, future training plans might need to be developed to be more sport specific.

In the future, sport specific strength needs to be done for both speed and technical skiers because these two sports differ in both knee angular velocities and in forces (Alhammoud et al., 2020). Therefore, it may be interesting to know how the strength training should be adapted for each group. According to Alhammoud et al. (2019) there were no technical, speed or gender differences between the groups in different concentric velocities and eccentric muscle work. However, since they only performed open kinetic chain, single joint tests and not with isometric actions this should also be performed in a closed kinetic chain, multi-joint test.
5 Conclusion

The aim of this study was to investigate the alpine strength profile to find evidence in what sport specific strength might be. This study presented evidence that sport specific strength for alpine elite skiers may primarily consist of isometric strength, training in slow concentric velocities and eccentric training. The results indicate that the sport specific strength for alpine elite skiers does not include concentric training in moderate and fast concentric movements. Explosive training methods need to be developed to train explosive eccentric strength since fast concentric movement is not specific for alpine skiing. Explosive eccentric strength may be vital for performance since skiers need to activate the muscle in different muscular movements. Since the study also found significant differences in RSI, the reaction strength is something that also appears specific for alpine elite skiers.

These results give coaches guidelines in how they can set up the strength and conditioning training during the dryland season when they want to highlight sport specific training. The results can be used as a basis for how sports specific training can be developed. Given the movement patterns from this study, jumping, with the concentric phase in focus, may not be specific for alpine elite skiers. During sport specific strength training for the lower extremity the movement pattern in the exercises should slow to fast in the eccentric and slow in the concentric phase. Thought, variation in the choice of exercises should always be advocated.
References


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