Competitive Performance Prediction of Elite Alpine Skiers

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Umeå 2019
I dedicate this dissertation to my parents, who have always believed in me and through their love and support made the completion of this dissertation possible.
Table of Contents

Abstract ................................................................................................................................. iii
Abbreviations ....................................................................................................................... v
Sammanfattning på svenska ................................................................................................. vi
List of publications .............................................................................................................. viii

Introduction .......................................................................................................................... 1

Background ............................................................................................................................ 3
  Competitive alpine skiing ..................................................................................................... 3
    Slalom ............................................................................................................................. 3
    Giant Slalom ................................................................................................................... 3
    How competitive performance is quantified ................................................................... 4
  The competitive season and structuring of on-snow training ........................................... 4
  On-snow training ............................................................................................................... 4
  Characteristics of alpine skiers ......................................................................................... 5
    The career of elite alpine skiers ..................................................................................... 5
    Body composition and skiing performance ................................................................... 5
  Forces, muscular activity and movement speed during skiing ......................................... 6
    Forces ............................................................................................................................ 6
    Muscular activity .......................................................................................................... 6
    Isometric and eccentric muscle strength ....................................................................... 7
    Movement speed .......................................................................................................... 7
  Aerobic and anaerobic capacity ....................................................................................... 8
  Balance ............................................................................................................................. 9
  Core strength and core stability ....................................................................................... 10
  Flexibility .......................................................................................................................... 10
  Physiological testing in alpine skiing ............................................................................. 11
  Summary ........................................................................................................................... 16

The rationale for the thesis ................................................................................................ 17

Aims ...................................................................................................................................... 18
  Specific Aims .................................................................................................................... 18

Materials and Methods ...................................................................................................... 19
  Study design ..................................................................................................................... 19
  Participants ....................................................................................................................... 20
  Testing procedures .......................................................................................................... 21
    One Repetition Maximum tests ...................................................................................... 21
    Hand Grip Strength ....................................................................................................... 22
    Pull-ups ........................................................................................................................... 22
    Brutal Bench .................................................................................................................. 23
    Change of Direction Speed ........................................................................................... 23
    20m Sprint test ............................................................................................................... 23
    Jump tests ....................................................................................................................... 23
    Force-Velocity Bike Test ............................................................................................... 24
<table>
<thead>
<tr>
<th>Test</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y Balance Test™</td>
<td>24</td>
</tr>
<tr>
<td>Lateral Box Jump 90-s</td>
<td>25</td>
</tr>
<tr>
<td>500 meters Rowing Ergometer Test</td>
<td>25</td>
</tr>
<tr>
<td>Peak Oxygen Uptake</td>
<td>25</td>
</tr>
<tr>
<td>Anthropometric tests</td>
<td>26</td>
</tr>
<tr>
<td>Fédération Internationale de Ski points</td>
<td>26</td>
</tr>
<tr>
<td>Statistics</td>
<td>27</td>
</tr>
<tr>
<td>Bivariate analysis</td>
<td>28</td>
</tr>
<tr>
<td>Multivariate analysis</td>
<td>28</td>
</tr>
<tr>
<td>Ethical statement</td>
<td>29</td>
</tr>
</tbody>
</table>

**Results**                                                                 | 30   |
| Paper I                                                               | 30   |
| Paper II                                                              | 31   |
| Paper III                                                            | 33   |

**Discussion**                                                            | 34   |
| Why is there a lack of predictive power on a group level?              | 34   |
| How important is the physiological dimension?                         | 36   |
| Is there an assumption of validity?                                   | 38   |
| Validity and reliability of physiological tests in alpine skiing      | 38   |
| Methodological considerations                                         | 40   |
| Other dimensions                                                     | 40   |
| Menstrual cycle effects                                               | 41   |
| Other predictive modeling procedures                                 | 41   |
| More tests specifically designed for alpine skiers                    | 41   |
| Fédération Internationale de Ski points                               | 41   |
| The novel approach of this thesis                                     | 42   |
| Application in sports                                                | 42   |

**Conclusion**                                                            | 43   |

**Acknowledgments**                                                       | 44   |

**References**                                                            | 46   |
Abstract

**Introduction** Competitive alpine skiing is a multifaceted and challenging sport that places high demands on its practitioners. To achieve competitive success, alpine skiers must master a variety of physical, technical, mental and social skills. Among the physiological qualities that have been described as necessary for elite performance in alpine skiing are qualities such as muscular strength and endurance, power, aerobic and anaerobic capacity, balance, core strength and core stability as well as flexibility. Testing these qualities can therefore be important, not only in order to optimize physiological training but ultimately to maximize the sport-specific performance of the individual athlete. Although several individual tests have been shown to correlate with skiing performance, the combined importance of a selection of tests, referred to as “test batteries”, has rarely been investigated. As a consequence, these test batteries risk misleading both athletes and coaches when planning and implementing preparatory training. Also, by using results from these tests, prediction of future performance is difficult. To generate useful results, a test protocol must be valid and reliable. Without taking this into account, significant resources seem to be invested in non-relevant tests each year, wasting important resources for clubs and federations as well as valuable time for athletes and coaches. Therefore, the development of valid test protocols is essential for all sports. The overall aim of this doctoral thesis was to identify physiological and anthropometric variables valid for prediction of competitive performance in alpine skiing (indicated by FIS points).

**Method** Paper I-III in this doctoral thesis followed an experimental, hypothesis-generating design which included both junior and senior elite alpine skiers. In all papers, physiological and anthropometric test results (X-variables) were correlated with FIS points (Y-variables) in order to investigate the predictive power of physiological and anthropometric variables for competitive performance in alpine skiing. The significance of the included test results was examined using bivariate and multivariate data analysis.

**Results** The results of Paper I show that included aerobic test results, neither alone nor in combination with anthropometric variables, could predict competitive performance of junior elite alpine skiers. Principal component analysis shows that male and female junior alpine skiers could be separated based on test results but that none of the included tests were important for sport-specific performance. The best multivariate models reached $R^2 = 0.51$ to $0.86$ and $Q^2 = -0.73$ to $0.18$. While several significant regression models could be observed, none of these met the criteria for valid models. The lack of predictive power of observed prediction models was confirmed by cross-validation.
Paper II show that included physiological test results from the test battery Fysprofielen could not predict competitive performance of senior elite female alpine skiers. Principal component analysis shows that there is a high correlation between individual physiological test results and their corresponding Fysprofielen score points, indicating that they can be used interchangeably. The Mann-Whitney U test was not significant neither for SL nor for GS. This suggests that Fysprofielen score points (summarized as Fysprofielen Index) and competitive performance (indicated by FIS points) are independent. The best multivariate models for SL and GS reached \( R^2 = 0.27 \) to \( 0.43 \) and \( Q^2 = -0.8 \) to -0.17, indicating low predictive power for competitive performance (as confirmed by cross-validation). The results of Paper III show that included physiological test results from a novel test battery could not predict competitive performance of senior elite female alpine skiers on a group level. When data were analyzed on a group level, the best models for SL and GS reached \( R^2 = 0.39 \) to \( 0.40 \), \( Q^2 = 0.15 \) to 0.21, indicating low predictive power. In contrast, when data were analyzed on an individual level, valid models with high predictive power (\( R^2 = 0.88 \) to \( 0.99 \) and \( Q^2 = 0.64 \) to \( 0.96 \)) were generated. A comparative analysis between individual OPLS models shows that the relative importance of different physiological qualities for athletic performance varies between skiers.

**Conclusion** When applying tests on alpine skiers, a holistic approach should be considered. This because competitive performance in alpine skiing is the result of a number of interacting dimensions. Before applying physiological tests, the validity and reliability of the test protocols must be determined. Administering tests that do not meet these criteria will probably waste not only important resources for clubs and ski federations but also risk misleading coaches and athletes when planning and implementing preparatory training.
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>1RM</td>
<td>One Repetition Maximum</td>
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<tr>
<td>BMI</td>
<td>Body Mass Index</td>
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<tr>
<td>C</td>
<td>Combined</td>
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<tr>
<td>CMJ</td>
<td>Countermovement Jump</td>
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<td>CMJa</td>
<td>Countermovement Jump with arm-swing</td>
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<tr>
<td>DXA</td>
<td>Dual-Energy X-ray Absorptiometry</td>
</tr>
<tr>
<td>DH</td>
<td>Downhill</td>
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<tr>
<td>FIS</td>
<td>Fédération Internationale de Ski</td>
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<td>GS</td>
<td>Giant Slalom</td>
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<tr>
<td>GRF</td>
<td>Ground Reaction Force</td>
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<tr>
<td>MVDA</td>
<td>Multivariate Data Analysis</td>
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<tr>
<td>OPLS</td>
<td>Orthogonal Projections to Latent Structures</td>
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<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
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<tr>
<td>SC</td>
<td>Super Combined</td>
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<tr>
<td>SIMCA</td>
<td>Soft Independent Modeling of Class Analogy</td>
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<tr>
<td>SL</td>
<td>Slalom</td>
</tr>
<tr>
<td>SG</td>
<td>Super Giant Slalom</td>
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<tr>
<td>SOC</td>
<td>Swedish Olympic Committee</td>
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<tr>
<td>VO\textsubscript{2max}</td>
<td>Maximal Oxygen Uptake</td>
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<td>VO\textsubscript{peak}</td>
<td>Peak Oxygen Uptake</td>
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Introduktion Tävlingsmässig alpin skidåkning är en mångfacetterad och utmanande idrott som ställer höga krav på dess utövare. För att uppnå tävlingsmässig framgång måste alpin skidåkare uppfylla olika fysiolologiska, tekniska, mentala och sociala fardigheter. Bland de fysiolologiska egenskaper som har beskrivits som viktiga för prestationer i alpin skidåkning återfinns fysio-styrkor, utåthållighet, power, aerob och anaerob kapacitet, balans, bälstyrka och bälstabilitet samt flexibilitet. Att testa dessa kvaliteter kan därför vara viktigt, inte bara för att optimera fysioterapeutisk träning utan också för att maximera idrottarens grenspecifika prestationer. Även om enskilda fysiolologiska tester har visat sig korrelera med prestationer i alpin skidåkning har betydelse av kombination av tester (ofta benämnt som "testbatterier") sällan undersökt. På grund av detta riskerar dessa testbatterier att vilsleda både idrottnare och tränare vid planering och tillämpning av förberedande träning. Dessutom är möjligheten att predikera idrottsspecifik prestationer med hjälp av testresultaten låg. För att generera praktiskt användbara resultat bör testprotokoll ha hög validitet och reliabilitet. Trots detta tycks ändå betydande resurser satsas på icke relevanta tester varje år, något som slösar med viktiga ekonomiska medel för klubbar och förbund vilket underlättar för idrottnare och tränare. Av denna anledning är identifieringen av andra och reliabla testprotokoll viktigt för alla idrotter. Det övergripande syftet med denna doktorsavhandling var att identifiera fysiologiska och antropometriska variabler valida för prediktion av tävlingsmässiga prestationer i alpin skidåkning (där av管局 FIS-punkter).

**Slutsats** Vid tillämpning av tester på alpin skidåkare bör en holistisk ansats övervägas. Detta eftersom tävlingsmässig prestationsförmåga i alpin skidåkning är ett resultat av ett flertal interagerande dimensioner. Innan fysiologiska tester appliceras bör validiteten och reliabiliteten hos testprotokollen fastställas. Att administrera tester som inte uppfyller dessa kriterier kommer sannolikt inte bara slösa med viktiga resurser för klubbar och skidförbund utan riskerar även att vilseleda tränare och idrottare vid planering och implementering av förberedande träning.
List of publications

This doctoral thesis is based on the following original articles. They will be referred to by their roman numerals.

**Paper I**  

**Paper II**  

**Paper III**  

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Introduction

Competitive alpine skiing is a multifaceted and challenging sport that places high demands on its practitioners [134,149]. To achieve competitive success, alpine skiers must master a variety of physical, technical, mental and social skills [46]. During skiing, athletes may be subjected to immense physiological strains [78,113] and must, therefore, be able to display a broad spectrum of physiological qualities. Elite performance in alpine skiing is suggested as a result of a number of interacting qualities [7,41] including muscular strength and endurance, power, aerobic and anaerobic capacity, balance, core strength and core stability as well as flexibility [4,66,97,108]. Testing these qualities can therefore be important, not only in order to optimize physiological training but ultimately to maximize the sport-specific performance of the individual athlete [46,66]. An overview of influencing dimensions is exemplified in Figure 1.

![Figure 1](image.jpg)

**Figure 1.** Overview of dimensions that affect competitive performance in alpine skiing. An overview of dimensions that potentially affect competitive performance in alpine skiing (including potential unknown dimensions). The proportion of each dimension has not yet been determined. This doctoral thesis focuses on the physical dimension (physiological performance and anthropometric variables).

Over the years, several different testing protocols in alpine skiing have been used [66], many of them with the intention of evaluating the physical status of athletes before and after the racing season. These protocols usually include general evaluations of strength, power, mobility, and endurance, but some countries also use physiological tests specifically designed for alpine skiers [46,66,109]. Although several individual tests have been shown to correlate with skiing performance (Table 1), the combined importance of a selection of tests, referred to as "test batteries", has rarely been investigated. As a consequence, these test batteries risk misleading both athletes and coaches when planning and
implementing preparatory training. Also, by using results from these tests, prediction of future performance is difficult.

To be useful, a test battery intended for a specific type of athlete must be valid and reliable [96]. Still, substantial efforts seem to be spent on non-relevant tests each year, wasting both financial resources as well as valuable time for athletes, coaches, and training advisors alike. Therefore, the development of valid test protocols is essential for all sports. This thesis focuses on alpine skiing, with the overall aim to identify physiological and anthropometric variables valid for prediction of competitive performance (indicated by FIS points). Through a multivariate statistical approach and validation of models, the results and analytical methods presented in this thesis can hopefully contribute to the future development of more relevant testing procedures for alpine skiing and other sports as well.
Background

Competitive alpine skiing

Competitions for elite alpine skiers are organized by the Fédération Internationale de Ski (FIS) and include FIS World Championship, FIS World Cup and Continental Cups. Alpine skiing has been an Olympic sport since its debut in the Winter Olympic Games 1936 [144] and now consists of six different disciplines including Slalom (SL), Giant Slalom (GS), Super Giant Slalom (SG), Downhill (DH), Combined (C) (or Super Combined (SC)) and the Team event [145]. The disciplines are divided into different categories, of which SL and GS are referred to as the technical disciplines, and SG and DH are referred to as the speed disciplines. Each of these disciplines differs from each other, mainly by different turning radius, speed, the length of the course and the vertical distance between the gates. FIS regulates the standards of each discipline which differs based on age and gender [37]. As the focus of this thesis is on SL and GS, other disciplines are not described in detail.

Slalom

Slalom (and GS) consist of two consecutive runs conducted on the same slope but with two different courses where the skier with the fastest combined time wins. Slalom is the shortest event, lasting 45-60 s and are usually conducted in relatively steep paths with speeds ranging from 20-60 km·h⁻¹ [7,41]. In SL, a race course is composed of a series of gates by alternating pairs of red and blue poles [37]. For the Winter Olympic Games, FIS World Championships and FIS World Cup, an SL course must have a vertical drop of between 140-220 m and be comprised by approximately 55-75 gates for men and between 40-60 gates for women. Each gate should be located at a relatively close distance to each other (4-13 m), forcing skiers to conduct quick and tight, short radius turns. Unlike the other disciplines, each gate in SL consists of just one pole, which allows skiers to follow a tight race line by cross-blocking the gates with their hands or repress them with the shin guards. By using this technique, athletes can ski close to, or even crossing the gates, in order to limit the intended skiing path [75].

Giant Slalom

Giant Slalom events are often conducted in relatively steep and undulating terrain in courses covering the entire width of the slope. A GS run usually lasts between 60-90 s [7] with speeds between 60-90 km·h⁻¹ [66]. In GS, SG, and DH, each gate consists of four slalom poles and two gate panels [37]. As for SL, the course setting for GS and SG is regulated via the vertical drop distance of the course [44]. According to the FIS regulations [37], a GS course must have a vertical drop of
250-450 m (up to 400 m for women) and direction changes equal to 11-15% of the altitude change for the race course.

**How competitive performance is quantified**

Competitive performance in alpine skiing is quantified by the FIS point scoring system and is used to regulate starting positions in all disciplines. Fédération Internationale de Ski points are calculated according to the alpine formula and are organized so that the best skiers in the world in each discipline have 0 (zero) points and that those placed 30 have 6 points [38]. In brief, FIS points is calculated according to the following formula: 

\[ P = \left(\frac{F \times T_x}{T_o}\right) - F \]

where \( P \) = FIS points, \( T_x \) = time for qualified competitor in seconds, \( T_o \) = time of the winner in seconds and \( F \) = factor for each discipline (which is announced annually by FIS) [38]. The FIS points lists are adjusted several times each year and apply to all athletes participating in FIS alpine skiing events.

**The competitive season and structuring of on-snow training**

The FIS official competition calendar for alpine skiing starts on July 1 and extends until June 30 the following year [39]. For most elite skiers, the competitive season starts in October/November and ends in the middle of March [46]. During a transitional period lasting from the end of the competition season until mid-April, many athletes continue their on-snow training before transitioning to physical preparation training that lasts from May until the end of July [42]. From August until the competition season starts, the focus is on on-snow training which is alternated with recovery periods and physical training aimed at maintaining the general physical fitness and increasing the sport-specific performance [42,46].

**On-snow training**

Elite alpine skiers usually train and compete for 130-150 days during a competitive season [46]. For skiers who specialize in the technical disciplines, approximately 120-140 of these are training days, and the remaining are competition days. For speed specialists, the number of training and competition events amounts to approximately 100-120 days in one year [46]. Usually, training sessions are conducted in the morning due to favorable snow conditions and low temperatures. A typical training session lasts between 2-4 hours which include recovery between training runs and lift transports [66,123].

During ski training, athletes usually perform between 1-5 warm-up runs, one inspection run of the training course and between 3-12 training runs depending on the discipline [46,66]. A SL training session typically consists of 2-12 runs and up to 700 turns in total. During a GS training, skiers usually perform up to 12
runs and a total of up to 600 directional changes while a SG training often consists of 2-8 runs and up to 300 turns depending on the number of runs and the length of the course. Like SG, a DH training usually consists of up to 8 runs and, depending on the training venue, between 100-280 directional changes in total [46].

**Characteristics of alpine skiers**

*The career of elite alpine skiers*

The career of professional alpine skiers seems to get longer. Throughout 40 years (from 1967-71 to 2009-13), the average age of medalists during the major alpine skiing competitions (FIS World Championships and the Winter Olympic Games) was extended by about five years (from 20.7 to 25.8 years for women and from 24.3 to 28.7 years for men) [118]. Speculative, the reasons for this development may be due to, e.g., improved training methods (on-snow training and preparatory training), development of surgical procedures and rehabilitation strategies in case of injuries and an increased opportunity to make a living on the sport (thanks to a larger amount of prize and sponsor money).

*Body composition and skiing performance*

Body composition is an important determinant of performance in many sports [89]. However, the requirements in different sports are often unique and require specific body compositions for them to be advantageous. While endurance athletes such as triathletes [49] and distance runners [79] usually benefit from relatively low body mass and low body fat percentage, basketball players generally have the advantage of being tall [141] and having a larger amount of lean body mass. In alpine skiing, anthropometric variables such as body fat percentage [3,8,55,100], body weight [3,8,19,55,97,152,154], body stature [3,64], lean body mass [55,97], leg length [127] and somatotype [32,149,152] have all been suggested to affect the competitive success of athletes. For example, one study [64] examined the difference in anthropometric variables between skiers, based on their placing during one so-called Olympic cycle (including the Winter Olympic Games, FIS World Cup, and FIS World Championships between the years 2006 and 2010). While the researchers did not find any statistical difference between skiers ranked top 30 in any of the investigated disciplines, they observed a significant difference in stature and BW when comparing top 10 between the disciplines SL, GS and C among those who placed over the top 30. As such, these results indicate that it may be more beneficial to be shorter and lighter in disciplines such as SL [55,64], while longer and heavier skiers are likely to have an advantage in disciplines such as DH [55,64,97]. These results also suggest that
differences in body composition [64] or somatotype [32] can potentially discriminate between athletes at different levels.

During the years, successful alpine skiers have seemingly become taller and heavier [97,100,154]. In a classical study by Eriksson, Ekholm, Hulten, et al. [33], the researchers found that skiers who were part of the Swedish national team between 1965-1975 had an increase in both body weight and body stature, from 64 to 76 kg and 168 to 178 cm, respectively. These results were later supported by interventions showing that the average body weight among U.S national female alpine skiers had increased from ~58 [55] to 66 kg [116] and that the body weight in the Swedish men's national alpine team had increased to 81 kg on average [12]. However, based on more recent studies [52,67,91,154], and despite some exceptions [97], this development seems to have stagnated.

An explanation for the previous development has been proposed as a result of the change in ski technique and the introduction of breakaway poles [155]. As the poles could be passed through instead of being forced around them, this likely favored skiers with higher body weight [155]. Although changes to alpine skiing have been made since then, e.g., the introduction of the carving ski [62], none of which has seemingly meant a fundamental change in the requirements of athletes body size or body composition. An exception to this is speed discipline specialists, where a larger amount of upper body muscle mass [97] or of being heavier in general probably is beneficial [47,136,152].

**Forces, muscular activity and movement speed during skiing**

**Forces**

There is a number of different forces acting on the athletes during a run. Among the most important of these are gravity, ski-snow friction, air drag, centripetal and centrifugal force [56,130]. Forces generated during alpine skiing vary depending on discipline [45,47] and are affected by factors such as speed, turning radius and body weight of the athlete [42,59]. Studies conducted during skiing as well as mathematical calculations indicate that skiers may be subjected to ground reaction forces (GRF) of 2-4 times the BW in both SL and GS [78,113,135] and that peak GRF can reach 3 times of the athletes BW during a regular SG and DH run [45,48].

**Muscular activity**

The ability to withstand these forces while maintaining balance and control is crucial for the competitive success of an alpine skier [66] and requires a significant contribution and coordination of muscle structures in the trunk and
lower extremities [59,66,136]. Monitoring of electromyographic (EMG) activity shows that muscle structures such as the tibialis anterior, erector spinae, gluteus maximus, hamstrings, and quadriceps muscle groups are highly activated during different turning phases [59,74,136] and that several antagonists muscles help to stabilize the knee and hip joints during the completion of a turn [59]. Studies also show that the regimen for muscular activity ranges between 50–280% of maximum voluntary isometric contraction (MVC) in investigated disciplines [59,60], indicating that large forces occur and that high levels of isometric and eccentric muscle strength could be essential to maintain performance [42].

Isometric and eccentric muscle strength
Not surprisingly, elite alpine skiers demonstrate significant leg strength during both isometric [55,73] and eccentric muscle actions [1,12,143]. When compared to other athletes, alpine skiers tend to have superior strength during low angular velocities and static muscle contractions [55,73,148]. However, as the angular velocities increases, this difference diminishes, suggesting a specific neuromuscular adaptation to loading patterns associated with skiing [148]. Studies conducted on elite and sub-elite skiers also indicate that more successful skiers tend to have higher maximum torque output and smaller hamstring-to-quadriceps (HQ) ratio compared to those competing at lower levels [1,19]. However, when scaled for body mass, differences in isometric and concentric strength between these practitioners seem to be alleviated [1]. As such, eccentric muscle strength has been proposed as a predictor of performance in alpine skiing [12,143].

Movement speed
The skiing turn itself can be divided into various phases that typically include the initiation, turning, completion and the transition phase [66]. Each of these phases differs from each other in terms of physical and technical requirements [66] and can, therefore, be categorized based on visual analysis or interpretation of EMG data [59]. The execution of a complete turning cycle takes about 1.4 – 4.1 s (depending on discipline) [11] and usually requires a shift from isometric-eccentric muscle work at the beginning of the turn to a concentric muscle action at the completion and transition to the next [66]. During such transitions, the average joint angle values of the hip, the inner leg and the outer leg ranges between 81-129°, 101±16°, and 114±26° respectively [118]. In addition, contrary to the notion that alpine skiing is an explosive sport, research shows that the joint angular velocity at SL, GS, and SG usually are below 200° s⁻¹ [59,74], which is significantly slower compared to those of martial arts athletes and professional sprinters who can reach 1000° s⁻¹ [13,43].
**Aerobic and anaerobic capacity**

The relative importance of aerobic versus anaerobic capacity for alpine skiing performance has long been a matter of debate [4,16,55,73,90,97,106,127,132,155]. For many years, high aerobic capacity was considered critical for the competitive success of skiers [106,132], probably due to the high VO\textsubscript{2max} test results [73] recorded on dominant skiing star Ingemar Stenmark [42,90]. While some scientific findings support this assertion [55,97,127,159], others have failed to establish aerobic capacity as a discriminating physiological variable between skiers at different performance levels [19,154]. Instead, several researchers have reported a correlation between anaerobic test results and skiing performance [5,19,93,131,155,161,162].

Because a majority of alpine skiing racing events last between 45-120 s [42], both the aerobic and the anaerobic energy systems will be utilized [42,66]. Studies show that the average energy requirement during high-intensity skiing varies between 80-200% of maximal oxygen uptake (VO\textsubscript{2max}) depending on discipline [122,142,151]. When differentiating the total energy supply, calculations indicate that the aerobic energy system accounts for 30-54% of the energy required during a SL or GS run [122,151]. Studies also suggest that differences in ski technique [21,121], mechanical and metabolic stress [41], as well as the overall skill of athletes, affect the relative contribution of the energy systems [123,151]. As such, these results further emphasize the intermediary relationship between the aerobic and anaerobic abilities of alpine skiers compared to pronounced endurance athletes [42].

Studies on alpine skiers show that the average VO\textsubscript{2max} values range from ~ 53 to 68 ml·min·kg\textsuperscript{-1} for males and ~ 46 to 57 mL·kg\textsuperscript{-1}·min\textsuperscript{-1} for female athletes [4,55,73,97,108,129,151]. Although many of these skiers exhibit relatively high aerobic test values, even when compared to elite cyclists and distance runners [54], high VO\textsubscript{2max} values are considered more a result of endurance training adaptations than a representation of real demands of the sport [72].

The consensus of published studies seems to be that both aerobic and anaerobic capacity is essential for maximum performance in alpine skiing. Although many researchers suggest that skiers should focus on training aimed at increasing their anaerobic capacity, the energy systems relative importance for racing performance on a group level has not yet been established. While most scientific findings indicate that aerobic capacity is not a limiting physiological factor for competitive performance, complementary aerobic endurance training can still be valuable as aerobic energy metabolism contributes up to ~50% of the energy demands during a run. In addition, a high aerobic capacity will likely allow athletes to tolerate higher blood lactate levels [80], faster recovery between
training runs and help to maintain competitive performance over an extended period of time [97].

**Balance**

Today's alpine skiing is highly demanding and therefore requires athletes to display a wide range of spatial and proprioceptive abilities [111]. As skiing events are often performed in challenging and ever-changing environments, athletes must continuously compensate for high internal and external forces in order to maintain balance and postural control [160]. As a result, a good balance has been proposed as imperative for both competitive and recreational skiers [85,160]. In sports such as basketball and soccer, an excellent balance can be essential in order to prevent injuries [18]. However, if this also applies to alpine skiing, or if the balance is important for the sport-specific performance of alpine skiers, remains to be proven [65,102].

Biomechanical studies suggest that a poor balance can adversely affect skiing performance [40,56], primarily by initiating compensatory body movements that ultimately leads to less than optimal skiing technique and lower force production [102]. While these results support the general perception of superior balance for alpine skiers, others have shown that elite skiers often perform comparatively or, in some cases, worse at both static and dynamic balance tests when compared to less skilled counterparts [99]. These contradictory results may be due to unspecific testing protocols (tests conducted in a laboratory environment) or that the balance tests used were not challenging enough to distinguish between skiers at different levels [102,140].

When balancing tests on experienced skiers are performed in skiing boots, the balance focus of these athletes seems to be shifted from the ankles to more hip involvement [98]. Also, experienced skiers seem to have similar balance performance with and without skiing boots [98], suggesting sport-specific balance abilities that cannot be tested using standard balance testing procedures [102]. When more specific balance tests for alpine skiers were applied, they proved reliable and sensitive, even for top-level skiers [102].

Collectively, testing the balance of alpine skiers in a laboratory environment is complicated because of the complex demands of the sport. Skiing usually takes place in a squatting position, which directs the balance towards the hip, while common balance tests drive towards testing the ankles. During skiing, athletes are subject to considerable internal and external forces, requiring constant adjustment of the balance on the skis, which is hard to replicate in a laboratory setting. Hence, to distinguish between competitive and recreational skiers, balance tests must be both specific and highly challenging.
Core strength and core stability

Core strength and core stability are common topics in the field of sports performance research [57,112,157]. Although the terms are often used as synonyms, they are in reality fundamentally different [36,57]. Whereas core strength generally refers to the ability of the trunk muscles to generate contractile force [36], core stability can be defined as the ability of the spinal stabilization system to maintain the lumbopelvic region in a physiologically neutral position during static and dynamic conditions [101]. Today, core strength and core stability training is an integral part of many sports conditioning programs [24,70] and is generally considered important also for alpine skiers [51,58,66,97].

Studies of core strength and core stability on alpine skiers have mainly included tests of isometric back flexion and extension strength [105,110]. While some of these studies have indicated that core training may be necessary for injury prevention [84,110], no one has yet been able to establish core strength or core stability as important physiological qualities for competitive performance [58]. However, these results are not surprising since alpine skiing is a highly dynamic sport [58,66] that does not require a significant contribution from muscle structures such as external obliques and rectus abdominis [59] (which indirectly suggests a lack of specific testing procedures) [57]. Furthermore, as for other sports, the importance of core strength and core stability for alpine skiing performance can be difficult to determine because core training is practically never performed in isolation and therefore cannot be established as the performance-enhancing factor [112].

Despite the lack of substantial scientific evidence supporting core strength and core stability as essential for competitive performance, alpine skiers (especially those with limited on-snow training time) may still benefit from specific core training as the core muscles help to maintain balance and control during skiing [58,66,160]. However, even though specific core training is also suggested to have other benefits (such as injury prevention) [84,110], alpine skiers should probably focus mostly on free-weight exercises such as squats and deadlift as these seem to entail higher core muscle activation and greater overall improvement of athletic performance [10].

Flexibility

Flexibility in an anatomical context refers to the range of motion (ROM) in joints and is reflected by the ability of an individual to move without any musculoskeletal limitations [76]. In alpine skiing, sufficient flexibility presumably allows athletes to adopt an efficient skiing position without undue strain on stabilizing structures [42]. In a study by Song [127], junior skiers were found to have higher overall flexibility in investigated structures compared to age-
matched controls. While some have suggested flexibility as an essential quality for alpine skiers [42], studies have yet to find a difference between practitioners across performance levels [4,19].

**Physiological testing in alpine skiing**

Physiological testing in alpine skiing is common [66,109], yet the practical usefulness can be questioned, which is discussed throughout this thesis. One crucial aspect to understand is the complexity of testing physiological capacities. Often a wide range of different tests are required to evaluate physiological qualities, potentially affecting performance. In addition, many tests are correlated (e.g., intercorrelated) and therefore, in an overall assessment of physiological performance, only one representative test for each capacity may be needed (Figure 2). This can be referred to as a reduction of dimensions, and in statistical terms deemed principal component analysis (PCA), which we will return to later.

Although elite athletes often perform better on certain physiological tests when compared to their less skilled counterparts, these findings are rarely an adequate measure of true sport-specific performance.

![Graph showing correlation between CMJ and SJ](image)

**Figure 2. Correlation between Countermovement Jump and Squat Jump.**

A significant positive correlation was observed between Countermovement Jump and Jump Squat ($R^2 = 0.90$, $p < .001$). This correlation indicates that as Countermovement Jump increases, Squat Jump tends to increase. Thus, only one of the tests are needed, or useful, in an overall evaluation of lower-body power.

A selection of studies that have investigated the correlation of physiological and anthropometric variables to competitive performance in alpine skiing can be
found in Table 1-2. As this thesis focuses on variables that affect skiing performance, only studies that met the following criteria were selected:

- Physiological performance and anthropometric variables correlated to sport-specific performance (points/ranking or time trials)
- Non-descriptive data (e.g., comparisons between skiers on different performance levels)

In addition, studies were selected based on the following criteria:

- Subjects ≥ 14 years
- Peer-reviewed
- More than one publication per variable

The importance of the physiological variable was assessed as Yes (Y) and No (N):

- For Pearson’s correlation coefficient (in the following referred to as Pearson’s correlation); Y if variables were described as important, correlated and/or significant by the authors
- Correlation values outside the range r = ±0.5 were considered important
- For Multiple linear regression; Y if the variable was included in the model

**Table 1.** Physiological performance variables correlated to sport-specific performance (points/ranking or time trials).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Sex (n)</th>
<th>Level/Age</th>
<th>Outcome</th>
<th>Statistics</th>
<th>Important Y/N (notes)</th>
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<td>National+ Club</td>
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<td>Pearson’s correlation</td>
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<td>Turcotte [5]</td>
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<td>Junior + National</td>
<td>USSA ranking</td>
<td>Multiple linear regression</td>
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<td>von Duvillard and Knowles</td>
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<td>Junior</td>
<td>USSA ranking</td>
<td>Pearson’s correlation</td>
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<td>[162]</td>
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<td><strong>Aerobic Capacity</strong></td>
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<td>Neumayr, Hoernagl, Pfister</td>
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<td>Elite</td>
<td>FIS ranking</td>
<td>Simple linear regression</td>
<td>Y (Speed group, 1998)</td>
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<td>et al. [97]</td>
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</table>

M = Male; F = Female; Junior = age 14-17; Club = Skiers at club level; National = Skiers at national level; Elite = Skiers at international level
Table 2. Anthropometric variables correlated to sport-specific performance (points/ranking or time trials).

<table>
<thead>
<tr>
<th>Reference</th>
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**Lean body mass**

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**Somatotype**

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**Skinfold**

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M = Male; F = Female; Junior = age 14-17; Club = Skiers at club level; National = Skiers at national level; Elite = Skiers at international level
Summary

In summary, competitive events in alpine skiing are organized and regulated by FIS. Competitions for elite alpine skiers include; FIS World Championships, FIS World Cups, Continental Cups, and the Winter Olympic Games. Disciplines in alpine skiing all differ from one another in terms of turning radius, the length of the course and the vertical distance between the gates. The competitive season for elite athletes is generally in progress from October/November until mid-March. Elite alpine skiers usually train and compete for 130-150 days in a year. On-snow training is often conducted during the morning and often consists of between 3-12 runs depending on the discipline. During skiing, athletes are subjected to immense forces, causing significant contribution from, and coordination of, several interacting muscle structures. Alpine skiing requires a large number of isometric and eccentric muscle contractions. In contrast to a common belief, alpine skiing cannot be characterized as an explosive sport.

The career of professional alpine skiers appears to get longer. Alpine skiers also seem to have become heavier and taller, which may be due to changes in skiing technique and the induction of breakaway poles. Both the aerobic and the anaerobic energy systems are utilized during a run, but the relative importance of each energy system for alpine skiing performance is still a matter of debate. While balance, core strength, core stability, and flexibility have been proposed as important physiological qualities for competitive performance, current scientific findings do not support these assertions. Physiological tests can be important for governing organizations as well as for individual athletes. However, to be useful for world-class competitors, a physiological test battery should be validated against sport-specific performance. To date, only a few studies have investigated the correlation between a combination of physiological test results and skiing performance in alpine skiing (indicated by points/ranking or time trials).
The rationale for the thesis

The notion that specific physiological qualities are necessary for alpine skiing performance seems to lack solid scientific evidence. While several studies have found a correlation between individual physiological test results and points/ranking or time trails, few have examined the predictive power of a combination of test results (Table 1-2). Thus, the optimal combination and the true importance of physiological test results remain to be determined. To our knowledge, no previous studies have approached this issue using multivariate data analysis (MVDA). Hence, the scientific rationale for this doctoral thesis was to identify physiological and anthropometric variables valid for prediction of competitive performance in alpine skiing using a multivariate statistical approach.
Aims

The overall aim of this doctoral thesis was to identify physiological and anthropometric variables valid for prediction of competitive performance (indicated by FIS points).

Specific Aims

*Paper I* to investigate the predictive power of aerobic test results and anthropometric variables for competitive performance (indicated by FIS points) of junior elite male and female alpine skiers.

*Paper II* to investigate the predictive power of the national test battery of the Swedish Olympic Committee (Fysprofilen) and anthropometric variables for competitive performance (indicated by FIS points) of senior elite female alpine skiers.

*Paper III* to investigate the predictive power of a novel physiological test battery, or by individual physiological profiling, for competitive performance (indicated by FIS points) of senior elite female alpine skiers.
Materials and Methods

Study design

*Paper I-III* in this doctoral thesis followed an experimental, hypothesis-generating design which included both junior and senior elite alpine skiers. In all papers, physiological and anthropometric test results (X-variables) were correlated with FIS points (Y-variables) in order to investigate the predictive power of physiological and anthropometric variables for competitive performance in alpine skiing (Figure 3). The importance of the included tests was examined using bivariate and multivariate data analysis. Selection of tests was based on the following:

- *Paper I* - The importance of aerobic capacity for alpine skiing performance has long been a matter of debate. Whether disagreements are due to inadequate predictive power of aerobic capacity for skiing performance, or the use of less than optimal statistical methods is unclear. For the prediction of competitive performance of junior elite alpine skiers, we applied multivariate data analysis on commonly used aerobic test results.

- *Paper II* - Lack of predictive power using aerobic test results in *Paper I*, led us to the assumption that this was due to the inclusion of results recorded during only one physiological performance test. Therefore, we chose to analyze a commonly used test battery in Sweden (Fysprofilen) for prediction of competitive performance of senior elite female alpine skiers.

- *Paper III* - As a more complex test battery (Fysprofilen) could not predict alpine skiing performance, we chose to apply a novel test battery on senior elite female alpine skiers. The new test battery was based on previous research [5,15,32,88,127,162] and physiological reasoning regarding the performance demands in competitive alpine skiing.
Figure 3. Overall study design and project stages. The "X" marked boxes list physiological and anthropometric tests that were carried out during each study. The "Y" marked boxes list outcome variables that were used as an indication of competitive performance in each study. The arrow indicates the order in which the studies were conducted.

**Participants**

Physiological test results from two sample groups were included in this thesis. The participants included in *Paper I* consist of a total of twenty-three (n = 23) junior elite male and female alpine skiers (Table 3), and the participants included in *Paper II-III* consist of a total of fourteen (n = 12-14) senior elite female alpine skiers (all members of the Swedish national alpine ski team, which was the inclusion criteria) (Table 3). Participating athletes were tested multiple times each season dependent on training and racing schedule as well as federation decisions. Prior to each test occasion, all participants underwent a brief medical examination and completed a health questionnaire. Exclusion criteria for participation during each occasion were indicated forms of health status (e.g., disease or injury) or use of medication that could potentially adversely affect their health or performance. After being informed of the risks and possible discomforts that could occur during testing, all participants provided their written consent for participation, as stated in the corresponding ethical approval form.
Table 3. Descriptive values of participants included in Paper I-III

<table>
<thead>
<tr>
<th>Level</th>
<th>Paper</th>
<th>Sex (age/n)</th>
<th>Body mass (kg)</th>
<th>Body stature (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junior elite</td>
<td>Paper I</td>
<td>M (age 17, n = 10)</td>
<td>75.4 ± 5.3</td>
<td>178 ± 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M (age 16, n = 13)</td>
<td>69.3 ± 5.5</td>
<td>178 ± 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F (age 17, n = 6)</td>
<td>68.1 ± 3.7</td>
<td>170 ± 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F (age 16, n = 10)</td>
<td>69.7 ± 3.4</td>
<td>172 ± 4</td>
</tr>
<tr>
<td>Senior elite</td>
<td>Paper II</td>
<td>F (n = 14)</td>
<td>67.4 ± 3.6</td>
<td>171 ± 5</td>
</tr>
<tr>
<td></td>
<td>Paper III</td>
<td>F (n = 12)</td>
<td>67.9 ± 3.7</td>
<td>172 ± 5</td>
</tr>
</tbody>
</table>

M = Male; F = Female; Junior elite = Skiers at junior elite level; Senior elite = Skiers at senior elite level. Data as Mean ± SD.

Testing procedures

Physiological tests were conducted at the Section of Sports Medicine, Umeå University, Sweden (Paper I-III) and Bosön (the development center for the Swedish Sports Confederation), Lidingö, Sweden (Paper II). For Paper I, physiological testing was conducted during the summer break (June-July) and the autumn term (October-December). For Paper II-III, all physiological testing was performed either immediately after the previous (April-May) and prior to the upcoming competitive season (August-October). All physiological performance tests included in Paper II were performed according to guidelines described in the testing procedures for Fysprofilen [138]. In brief, Fysprofilen is a physiological test battery developed by the Swedish Olympic Committee and consists (for alpine skiing) of thirteen different performance tests.

Participants were instructed to avoid strenuous physical activities and adhere to the same routines regarding, e.g., sleep, water, and nutrition intake during the 24 hours before each test occasion. Prior to any physiological performance testing, participants performed a ~10-15 minutes warm-up protocol consisting of low-intensity jogging or cycling, lateral strides, jumps, sprints, and dynamic stretching exercises. Before each specific test, a self-regulated exercise-specific warm-up was also performed. These warm-ups were carried out with low to moderate intensity (e.g., before rowing 500m) or at low to moderate load (e.g., before back squats). Verbal encouragement was provided during all physiological performance testing to encourage participants to perform at their maximum potential. All performance tests were carried out with maximum effort or to volitional exhaustion. Physiological test results were assigned as X-variables in the statistical analyses.

One Repetition Maximum tests

The assessment of One Repetition Maximum (1RM) performance (tested with Back squats, Bench press and Cleans) was conducted using factory calibrated competition weights and barbells from Eleiko (Eleiko Sport, Halmstad, Sweden)
All 1RM performance tests were carried out using an incremental loading protocol (suggested load increase was (set x reps/percent of 1RM): 1 x 8/50%, 1 x 6/60%, 1 x 5/70%, 1 x 3/80 %, 1 x 2/90%, 1 x 1/100, 1 x 1/102%). Attempts were conducted until failure or voluntary discontinuation of more attempts on higher loads. The recovery time between attempts was standardized to ≥ 5 minutes.

A Back squats attempt was approved when the participants descended, with the top of their femur parallel to the floor, and back up to the starting position. A Bench press attempt was approved when the participants descended the barbell, from fully extended arms, down to the chest and back up to the starting position without bouncing the barbell on the sternum or by lifting the back of the bench. A Cleans attempt was approved when participants managed to clean the barbell in one explosive motion from the initial starting position, up to the anterior deltoids and catch it in an upright position. The best performance (kg) for each 1RM test was recorded. The 1RM tests for back squats [26,124,150], bench press [115,124], and cleans [26,35] are considered safe and reliable tests (ICC ≥ 0.91) for assessing strength in a number of different populations.

**Hand Grip Strength**
Maximal isometric hand grip strength was tested unilaterally using calibrated hand grip dynamometers (T.K.K. 5401 GRIP D (Takei Scientific Instruments Co., Ltd., Niigata, Japan) (Paper II) and Jamar Hydraulic Hand Grip Dynamometer (Patterson Medical, Warerville, IL, USA) (Paper III). A Hand Grip Strength test was approved when the participants squeezed the dynamometer with as much force as possible for 3 seconds. The best performance (kg) out of three attempts on each hand was recorded. The Hand Grip Strength test is considered a valid and reliable method (r ≥ 0.9 to criterion standards and ICC = 0.86–0.97, respectively) for monitoring hand grip strength of athletes [30].

**Pull-ups**
The Pull-ups test was conducted using a regular pull-up bar with a pronated hand grip position slightly wider than shoulder width (Paper II). A Pull-ups repetition was approved when the participants pulled themselves up until the chin was above the bar, without kipping of the body or legs or by changing the hand grip. The total number (n) of approved repetitions was recorded. The Pull-ups test is considered a reliable method (ICC = 0.96-0.99) for assessing upper extremity pulling strength [29].
Brutal Bench
The Brutal Bench test was conducted using a regular brutal bench (Paper II). A Brutal Bench repetition was approved when the participants managed to get up from the starting position, mark with their elbows against their knees and down back again without bouncing against the backrest in the bottom position. The total number (n) of approved repetitions was recorded. To our knowledge, the Brutal Bench test has not yet been validated.

Change of Direction Speed
The assessment of Change of Direction Speed (CODS) performance (tested with the Harre’s test and the Illinois Agility test (IAT)) was conducted using validated timing systems (PF MuscleLab MA4020e (Ergotest Innovation AS, Porsgrunn, Norway) [137] and IVAR Jump and Sprint system (Spin Test, Tallinn, Estonia) [23]). All CODS tests were performed three times with ≥3 minutes of rest between each attempt.

The Harre’s test was conducted following the procedures described in Hoyek, Champely, Collet, et al. [63] (Paper II). A Harre’s test attempt was approved when the participants completed the course as fast as possible without touching the center cone or the hurdles. The IAT test was conducted following the procedures described in Lacy [82] (Paper III). An IAT test attempt was approved when the participants completed the course as fast as possible without touching the markers or by taking a shortcut. The best performance (s) for each CODS test was recorded. To our knowledge, the Harre’s test has not yet been validated. The IAT is considered a reliable test (ICC = 0.85–0.98) for the assessment of CODS performance [53].

20m Sprint test
The assessment of 20m Sprint performance was conducted using the same timing equipment as for the CODS tests (Paper II). A 20m Sprint attempt was approved when the participants completed 20 meters as fast as possible. The best performance (s) was recorded. The 20m Sprint test is considered a reliable test (ICC = 0.91) for the assessment of sprint performance [95].

Jump tests
The assessment of jump performance (tested with Squat Jump (SJ), Countermovement Jump (CMJ) and Countermovement Jump with arm-swing (CMJa)) was conducted using validated infrared jump mat systems (PF MuscleLab MA4020e (Ergotest Innovation AS, Porsgrunn, Norway) and IVAR Jump and Sprint system (Spin Test, Tallinn, Estonia)). All jump tests were
performed as single jumps three times with ≥3 minutes of rest between each attempt.

The SJ test was conducted from a squatting position (at 90° knee angle) with the hands firmly placed on the hips (Paper II). A SJ test attempt was approved when participants, on the test leader’s command and without countermovement, jumped as high as possible and landed with normal knee flexion in the same position as the take-off. The Countermovement Jump tests were conducted from an upright position: the CMJ with the hands firmly placed on the hips and with countermovement (Paper II-III), the CMJa with countermovement and arm-swing (Paper II). A Countermovement Jump test attempt was approved when participants, on the test leader’s command, jumped as high as possible and landed with normal knee flexion in the same position as the take-off. The best performance (cm) for each jump test was recorded. The SJ and the CMJ are both considered reliable tests (ICC = 0.91-0.93) for the assessment of jumping performance [95].

**Force-Velocity Bike Test**
The Force-Velocity Bike Test (FVBT) was conducted from a standing start against a breaking weight equivalent to 2, 4, 6, 8, 10 and 12% of participants body weight using a friction-loaded Monark 894E Peak Bike (Monark Exercise, Varberg, Sweden) (Paper III). All sprints were conducted in a randomized order with ≥5 minutes of rest between each attempt. Peak power in absolute measurement (W) (PP), peak power relative to body weight (W·kg⁻¹) (RPP) and time to peak power (TTPP) for each sprint were recorded using Monark ATS Software (Monark Exercise, Varberg, Sweden). The best performance (PP, RPP, and TTPP) for 10 seconds during all sprints were used in the statistical analysis. The FVBT is considered a reliable test (ICC = 0.94-0.98) for the assessment of power in the lower extremities [68].

**Y Balance Test™**
The assessment of balance performance was conducted following the procedures described in Plisky, Gorman, Butler, et al. [107] using a Y Balance Test Kit™ (FunctionalMovement, Danville, VA, USA) (Paper III). A Y Balance Test™ (YBT) attempt was approved when the participants, on the test leader’s command, managed to reach out as far as possible and back without losing their balance or by lifting their heels from the center platform or by releasing their hands from their hips. The best performance (cm) on each foot in each of the three directions (anterior, posteromedial and posterolateral) was recorded. The YBT is considered a reliable test (ICC = 0.85-0.93) for the assessment of balance performance [126].
Lateral Box Jump 90-s
The Lateral Box Jump 90-s (LBJ90) test was conducted following the procedures described in von Duvillard and Knowles [162] using a wood-frame box with the dimensions of 40 cm high x 60 cm long x 50 cm wide (Paper III). A LBJ90 repetition was approved when the participants, starting from the top of the box, performed a lateral jump with both feet down on one side and then back up to the top of the box. The total number (n) of approved repetitions (back and forth over the box) for 90 seconds was recorded. The LBJ90 is considered a reliable test for the assessment of jump strength endurance of both male (ICC = 0.90) and female (ICC = 0.87) athletes [110].

500 meters Rowing Ergometer Test
The 500 meters Rowing Ergometer Test (500mRET) was conducted following the procedures described in Lindberg, Oksa, Gavhed, et al. [88] using a Concept2 Model D Indoor Rower (Concept2, Morrisville, VT, USA) (Paper III). The test was performed from a standing start using the highest resistance (spiral damper setting at 10). The time (s) to complete 500 meters, peak power (W) (PP) and mean power (W) (MP) was recorded. The 500mRET is considered a reliable test for the assessment of rowing performance (ICC = 0.99-1.0 to 0.80-0.98 for power output and overall rowing time, respectively) [128].

Peak Oxygen Uptake
The Peak Oxygen Uptake (VO₂peak) tests was conducted using either a programmable cycle ergometer (Monark 839E, Monark Exercise, Varberg, Sweden) (Paper I-III) or a running treadmill (Rodby RL2500E, Rodby Innovation, Hagby, Sweden) (Paper II-III). During both protocols, pulmonary gas exchange was measured continuously using a calibrated Oxycon Jeager Pro (mixing chamber mode setting) (CareFusion, Hoechberg, Germany). The highest mean value for VO₂ for 30 seconds was considered maximum and recorded as VO₂peak in both absolute rate (L·min⁻¹) (Paper I) and the relative rate (mL·kg⁻¹·min⁻¹) (Paper I-III). Heart rate (HR) was monitored using a Polar Electro S610i (Polar Electro Oy, Kempele, Finland) (Paper I-III). Fingertip blood lactate samples were collected during the last 30 seconds on each load (3-minute stages) and analyzed using a YSI 1500 Sport Lactate Analyzer (YSI Life Sciences, Yellow Springs, OH, USA) (Paper I).

For Paper III, VO₂peak was also estimated using the following prediction formula: VO₂peak (mL·kg⁻¹·min⁻¹) = 124.165 + (-0.748 * 500mRET (s)).
**Anthropometric tests**

For assessment of anthropometric variables, participants were instructed to wear only light clothing (e.g., t-shirt, sports bra, shorts, and tights). Body mass was measured to the nearest 0.1 kilograms using a standard digital weight scale (Soehle weights, Leifheit AG, Nassau, Germany) (*Paper I-III*). Body stature was measured to the nearest 0.1 centimeters using a wall-mounted body length meter (Fosamax stadiometer, Merck & Co. Inc., New Jersey, USA) (*Paper I-III*). Body mass index (BMI) (*Paper I*) was calculated using the following formula: \( \text{BMI} = \frac{\text{body mass (kg)}}{\text{stature (m)}^2} \). Body composition was measured using a phantom calibrated Dual-energy x-ray absorptiometry (DXA) Lunar iDXA scanner (GE Medical Systems Lunar, Madison, WI, USA; Encore Version 14.10.022) (*Paper III*). Due to a large number of variables recorded during a DXA scan, PCA was used to reduce the number of dimensions in the dataset. After visual inspection of the PCA plot, the following variables were selected as they appeared relevant: the total amount of fat mass (g), lean body mass (g), tissue mass (g), bone mass and body fat in percentage (%). Dual-energy x-ray absorptiometry is considered a valid method for the assessment of body composition in a variety of populations [2,14,119]. Anthropometric data were assigned as X-variables in the statistical analyses.

**Fédération Internationale de Ski points**

Fédération Internationale de Ski points used in this thesis were extracted from FIS point score lists published in December (6th list) and in April (11th list) each year (*Paper I-III*). The lists were selected because (1) they were published during the ongoing competition season, (2) results from the first competition in both disciplines were included and, (3) they represent a change in points/ranking data over time (Table 4). The points lists were obtained from the FIS official website at https://www.fis-ski.com/DB/alpine-skiing/fis-points-lists.html. Fédération Internationale de Ski points were assigned as Y-variables in the statistical analyses.
Table 4. Spearman’s correlation matrix (values as Spearman’s $r$) between FIS points lists in SL and GS for Swedish female skiers published during the season 2013/2014.

<table>
<thead>
<tr>
<th>Discipline</th>
<th>List</th>
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<th>5</th>
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</table>

Correlated lists contained only skiers who were listed as active. The critical values are 0.58, 0.71, and 0.82 for significance levels .05, .01, and .001 respectively. Lists published during other seasons may correlate between each other differently.

Statistics

Statistical calculations were conducted using JMP 13.1-14.0 (SAS Institute Inc, Cary, NC, USA) and SIMCA 14.0-16.0 (Sartorius Stedim Data Analytics AB, Umeå, Sweden).

For Paper I-II, Shapiro-Wilk goodness of fit tests investigated data distributions of physiological performance tests and anthropometric variables. Data were considered normally distributed if $p > 0.05$. For Paper III, distribution was assessed using SIMCA’s built-in tests for normality (skewness). The following variables had skewed distributions: Pull-ups ($W = 0.94, p = 0.004$) (Paper II), Stature (cm), Hand Grip Strength R (kg), YBT Posteromedial H (cm) and YBT Posterolateral L (cm) (Paper III). Variables that were skewed (based on an alpha of 0.05) were log$_{10}$ transformed to normality. After transformation, all variables exhibited a normal distribution.
**Bivariate analysis**

A Spearman’s rank correlation analysis was conducted in order to examine the relationship between physiological test results and FIS points in both SL and GS (*Paper I*). Cohen’s standard was used to evaluate the strength of the relationship: levels of effect size between $0.10$ and $0.29$ were classified as small, levels of effect size between $0.30$ and $0.49$ were classified as moderate, and levels of effect size above $0.50$ was classified as large. Spearman’s rank correlation is a nonparametric test that estimates how well the relationship between two variables can be described in the form of a monotonic function [27].

A Mann-Whitney $U$ two-sample rank-sum test was performed in order to investigate whether there were significant differences in physiological performance (indicated by Fysproffen Index) between the levels of ranking (Lowest and Highest) in both SL and GS (*Paper II*). The Mann-Whitney $U$ two-sample rank-sum test is a nonparametric alternative to the independent samples t-test but does not share the same assumptions of normal distributions [27].

**Multivariate analysis**

Principal component analysis was conducted in order to identify representative body composition variables (*Paper III*) and to detect trends and outliers in the data (*Paper I-III*). Principal component analysis is a statistical method used to identify trends and patterns as well as for visualizing and describing similarities and differences between variables in a multivariate dataset [34].

Orthogonal projections to latent structures (OPLS) was performed in order to examine regression and prediction of competitive performance (indicated by FIS points) from physiological test results (*Paper I-III*) (Figure 4). $R^2$ (goodness of fit) and $Q^2$ (goodness of prediction) measures were calculated for the overall assessment of all models. $R^2$ and $Q^2 > 0.60$ (less than $\leq 0.20$ difference between $R^2$ and $Q^2$) were considered valid [86] (*Paper I*). DmodX and Hotelling’s $T^2$ range plots were used to visually access the statistical significance of fitted models (*Paper II-III*). Shared and Unique Structures (SUS)-plots were generated in order to compare individual OPLS SL and GS models (*Paper III*). Cross-validation by permutation was used to visually assess the validity of each OPLS model (*Paper I-III*). In brief, when conducting a permutation test, class labels are permuted and assigned in a random order to different observations [153]. With incorrectly assigned class labels, a new model is then calculated. The assumption when conducting a permutation test is that permuted models should not be able to predict data well. Because all new models are based on random assignment of class labels, there should be no difference between them [153]. Thus, an original model with lower predictive power than a certain number of permuted models is probably not valid. All data were scaled according to Univariate (UV) scaling.
Orthogonal projections to latent structures is a robust statistical method used to generate models that describe the relationship between sets of variables in a multivariate dataset [34].

**Figure 4.** A simplified description of the OPLS procedure. $R^2$ is a measurement of goodness of fit. The procedure is used to estimate the relationship between one dependent variable (Y) and one or more independent variable (X). $Q^2$ is a measurement of goodness of prediction. $Q^2$ is calculated via cross-validation as follows: the dataset is divided into seven parts, where 1/7th of the data is removed each cycle in a systematic order. The remaining 6/7th of the data is then used to predict a new model. This procedure is repeated until a complete set of new models has been predicted. Thereafter, cumulated data is compared with the original model for the calculation of $Q^2$. The arrows indicate the theoretical order of the procedures.

**Ethical statement**

The ethical committee for Northern Sweden at Umeå University granted ethical permissions for *Paper I* (Dnr 2011-236-31M) and *Paper II-III* (Dnr 2016-260-31M) and the studies were conducted according to the guidelines expressed in the Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Subjects 2008 [146]. As strenuous exercise and maximal performance are part of the daily routines of elite athletes, included procedures, and all competitive results are openly published no ethical issues are visualized.
Results

*Paper I*

This study investigated the predictive power of aerobic test results and anthropometric data for competitive performance (indicated by FIS points) of junior elite alpine skiers. The study included physiological test results from twenty-three (n = 23) junior elite male and female alpine skiers. While principal component analysis indicated that male and female skiers could be separated based on their aerobic test results, none of the included variables were of significant importance for performance. The best multivariate prediction models reached $R^2 = 0.51$ to 0.86 and $Q^2 = -0.73$ to 0.18. Although several significant regression models could be observed, none of these met the criteria for valid models ($R^2 > 0.8, Q^2 > 0.5$, significance by R1 and “yes” for $Q^2$ cross-validation) (Table 2 in *Paper I*). The lack of validity of these models was confirmed via cross-validation by permutation. Also, an important finding in this study was that FIS points demonstrate a non-normal distribution when treated as continuous data. As such, this finding may be an explanation for inconsistent results among previous studies that have examined the importance of aerobic test results for alpine skiing performance (Table 1).

The lack of performance predictive power of included physiological test results in this study is exemplified in Figure 5-6.

Figure 5. Correlations between physiological test results and FIS points in SL and GS for thirteen junior elite male alpine skiers age 16. A) Orthogonal projections to latent structures visualize correlations between variables (X = 16, Y = 2, n = 13). Physiological test results and FIS points (labeled as rank) located in the same or opposite part of the loading plot are correlated. The horizontal axis displays the X- and Y-loadings of the predictive component, and the vertical axis the X- and Y-loadings for the first Y-orthogonal component. For example, a high value (max = 1) means that the component is aligned with the original variable, a value close to zero...
shows that it has no influence. A low value (min = –1) indicates the opposite influence. B) The X/Y overview plot shows the cumulated $R^2$ and $Q^2$ values for the model. The plot indicates a low predictive power ($R^2 = 0.25$ to 0.45, $Q^2 = -0.50$ to – 0.27).

**Figure 6. Correlations between physiological test results and FIS points in SL and GS for ten junior elite female alpine skiers age 16.** A) Orthogonal projections to latent structures visualize correlations between variables ($X = 16$, $Y = 2$, $n = 10$). Physiological test results and FIS points (labeled as rank) located in the same or opposite part of the loading plot are correlated. The horizontal axis displays the X- and Y-loadings of the predictive component, and the vertical axis the X- and Y-loadings for the first Y-orthogonal component. For example, a high value (max = 1) means that the component is aligned with the original variable, a value close to zero shows that it has no influence. A low value (min = –1) indicates the opposite influence. B) The X/Y overview plot shows the cumulated $R^2$ and $Q^2$ values for the model. The plot indicates a low predictive power ($R^2 = 0.65$ to 0.71, $Q^2 = -0.25$ to – 0.24).

**Paper II**

This study investigated the predictive power of the physiological test battery Fysprofilen for competitive performance (indicated by FIS points) of senior elite female alpine skiers. Fysprofilen is the official test battery of the Swedish Olympic Committee and consists of thirteen different tests divided into four main categories: strength, power, aerobic and anaerobic. The study included physiological test results from fourteen ($n = 14$) senior elite female alpine skiers. Principal component analysis demonstrated a high correlation between individual physiological test results and their corresponding Fysprofilen score points, indicating that they can be used interchangeably. The Mann-Whitney $U$ test was not significant for either SL ($U = 99.5$, $z = -0.07$, $p = 0.95$) or GS ($U = 80$, $z = -0.83$, $p = 0.41$), indicating that Fysprofilen score points (summarized as Fysprofilen Index) and competitive performance (indicated by FIS points) are independent. Generated OPLS models for SL and GS reached $R^2 = 0.27$ to 0.43 and $Q^2 = -0.8$ to -0.17, indicating low predictive power. Cross-validation by permutation confirmed the lack of validity of these models.
The lack of performance predictive power of included physiological test results in this study is exemplified in Figure 7-8.

Figure 7. Correlations between physiological test results and FIS points in SL for fourteen senior elite female alpine skiers between the years 2012 and 2014. A) Orthogonal projections to latent structures visualize correlations between variables (X = 15, Y = 1, n = 14). Physiological test results and FIS points (labeled as rank) located in the same or opposite part of the loading plot are correlated. The horizontal axis displays the X- and Y-loadings of the predictive component, and the vertical axis the X- and Y-loadings for the first Y-orthogonal component. For example, a high value (max = 1) means that the component is aligned with the original variable, a value close to zero shows that it has no influence. A low value (min = −1) indicates the opposite influence. B) The X/Y overview plot shows the cumulated $R^2$ and $Q^2$ value for the model. The plot indicates a low predictive power ($R^2 = 0.43$, $Q^2 = −0.17$).

Figure 8. Correlations between physiological test results and FIS points in GS for fourteen senior elite female alpine skiers between the years 2012 and 2014. A) Orthogonal projections to latent structures visualize correlations between variables (X = 15, Y = 1, n = 14). Physiological test results and FIS points (labeled as rank) located in the same or opposite part of the loading plot are correlated. The horizontal axis displays the X- and
Y-loadings of the predictive component, and the vertical axis the X- and Y-loadings for the first Y-orthogonal component. For example, a high value (max = 1) means that the component is aligned with the original variable, a value close to zero shows that it has no influence. A low value (min = –1) indicates the opposite influence. **B) The X/Y overview plot shows the cumulated $R^2$ and $Q^2$ value for the model. The plot indicates a low predictive power ($R^2 = 0.39, Q^2 = -0.17$).**

**Paper III**

This study investigated the predictive power of a novel physiological test battery for competitive performance (indicated by FIS points) of senior elite female alpine skiers. The test battery was based on previous research and designed to cover a wide range of physiological and anthropometric qualities (e.g., strength, endurance, balance, and body composition). The study included physiological test results from twelve (n = 12) senior elite female alpine skiers. When data were analyzed on a group level, the best OPLS models for SL and GS reached ($R^2 = 0.39$ to 0.40, $Q^2 = 0.15$ to 0.21), indicating low predictive power. In contrast to **Paper II**, however, the included physiological test results in this study generated valid models (as confirmed by cross-validation by permutation). Importantly, when data were analyzed on an individual level, valid models with high predictive power were generated ($R^2 = 0.88$ to 0.99 and $Q^2 = 0.64$ to 0.96). In order to exemplify the unique individual profiles of equally top-ranked skiers, individual OPLS models for SL and GS were generated, and subsequently compared with the SUS plot analysis.
Discussion

The overall aim of this doctoral thesis was to identify physiological and anthropometric variables valid for prediction of competitive performance in alpine skiing. The main result of Paper I was that included aerobic test results, neither alone nor in combination with anthropometric variables, could predict competitive performance of junior elite male and female alpine skiers. The main result of Paper II was that included physiological test results could not predict competitive performance of senior elite female alpine skiers. Even when converted into separate score points or as a summarizing test score (Fysproffilen Index), the included tests failed to discriminate between skiers on an individual level. These results were confirmed in Paper III, where included physiological test results failed to generate OPLS models with high predictive power ($R^2$ and $Q^2 > 0.6$) for competitive performance of senior elite female alpine skiers on a group level. In contrast, when data were analyzed on an individual level, valid models with high predictive power could be generated. Collectively, findings indicate that none of the investigated physiological performance tests are predictive for competitive performance on a group level. Rather, ranking data and physiological test results must be collected over time and analyzed using individual profiling.

Why is there a lack of predictive power on a group level?

Competitive performance of alpine skiers is affected by a number of interacting factors [134,149], including the mental, social, technical and physiological dimensions [46]. As this thesis focus on physiology, other dimensions were not directly investigated, but are to some extent incorporated in the discussion. The significance of particular dimension varies between individuals, as exemplified by the SUS-plots of physiological variables in Paper III. Individual variations, and the lack of comprehensive testing of all dimensions, partially explain the lack of predictive power when analyzing data on a group level.

Another explanation for the lack of significant models may be due to the lack of a reliable outcome variable, as validity and reliability interact [6,31]. As stated by Currell and Jeukendrup [31], "A protocol can be reliable, but not valid, while a valid protocol must be reliable". These issues are discussed in more detail below. The reliability of the outcome variable (Y) affects the validity of the test protocol (X). In this thesis, FIS points were used as the outcome variable, an indication of competitive performance. As extensively discussed in Paper II, the ranking system has been criticized for not being fair (primarily because of how points are calculated) and encouraging an opportunistic behavior [92].
However, the main problem with the use of FIS points as an outcome variable is that individual differences in ranking points over time (Figure 9) are not exclusively due to changes in physiological performance (concluded in Paper I-III and exemplified in Figure 10). Factors such as starting order, participating competitors and previous race results also affect the ranking position. Hence, FIS points are probably not at any given time a reliable measure of physical performance. Consequently, no matter the reliability and validity in measurements of physical performance tests, prediction of competitive performance cannot be performed with high accuracy (closeness to the truth) and precision (closeness between repeated measurements). Thus, when data is analyzed on a group level, individual changes in terms of ranking will inevitably result in models with low predictive power. While other performance outcomes than FIS points could have been used (e.g., time trails during training and individual competition results), none of these represent true long-term competitive performance. Despite its apparent shortcomings, FIS points are currently the most reliable and valid indications of competitive performance over multiple competition seasons.

![Figure 9. Overview of the change of FIS points in GS between the season 2011/2012 until the season 2016/2017 for all participants included in Paper III. Data were extracted from the 11th FIS points list published each season. An upward trend indicates an improvement in FIS points while a downward trend indicates a deterioration. For ethical reasons and in order to protect each participants identity, the y-axis scale has been removed.](image-url)
Figure 10. Example of the individual change of FIS points in GS and physiological test results between the season 2011/2012 until the season 2016-2017. The plot is an example of the change of physiological performance and FIS points in GS for one of the participants included in Paper II-III. Ranking data was extracted from the 11th FIS point list published each season. Included physiological test results have been scaled proportionally to FIS points for an illustrative purpose. An upward trend indicates an improvement in performance while a downward trend indicates a deterioration. For ethical reasons and in order to protect the participant’s identity, the y-axis scales have been removed.

How important is the physiological dimension?

As shown in Figure 1, the physiological dimension is just one of several interacting dimensions affecting competitive performance in alpine skiing. As this thesis only investigated the importance of physiological test variables, the proportion of physiology in relation to athletic performance cannot be determined. High physiological performance is important in almost every sport [9]. The ability to generate high neuromuscular strength and power [54,133], high oxygen uptake [54], superior coordination and change of direction ability [20] are just some of the physiological qualities that often characterize top-level athletes. In alpine skiing, physiological qualities such as muscle strength, aerobic and anaerobic capacity, balance, core strength and core stability have all been proposed as prerequisites for elite performance [4,66,97,108]. These arguments have been supported by numerous studies [3,5,32,55,93,94,97,103,127,152,162], all finding significant correlations between physiological test variables and skiing performance.

As indicated by our results, these claims may not be valid. First and foremost, it can be concluded that competitive alpine skiing does not seem to require physiological qualities that can be classified as extreme in terms of human performance. If this were the case, some of the participants included in this thesis
would probably not belong to the absolute elite. Rather, our results show that athletes with significantly different physiological capacities can reach comparable elite level performance. In other words, one weakness can be compensated for by another strength. Also, in agreement with previous studies [19,99,102,140,154], our findings suggest that differences in competitive performance between groups of skiers cannot be explained by physiological test results alone. For example, in Paper I junior elite female skiers displayed similar peak VO₂ values as their higher-ranked senior counterparts, included in Paper II-III. Some studies have identified differences in physiological performance between skiers at different competitive levels [32,114]. However, this is no proof of causality; physiological characteristics may not be related to, or the reason for, the difference in ranking.

Furthermore, as discussed briefly in Paper II-III, there may be an issue with the choice of statistical method in the abovementioned correlation studies as almost all of these have applied Pearson’s correlation to ranking data. For example, as demonstrated in Paper I, FIS points is an ordinal variable based on a sigmoid function which, if assigned as continuous data, does not exhibit a normal distribution. However, as Pearson’s correlation assumes constant variance and linearity [25], it is unable to detect monotonic relationships in data. That is, applying Pearson’s correlation to this type of data may not be optimal. Another concern with published studies is the lack of cross-validation as this technique could have been used to assess the validity and reliability of observed correlations. As such, the results in some previous studies may be due to chance, which to a certain extent could also explain the inconsistent results reported in different publications.

The question one must ask is then; how important is the physiological dimension for alpine skiing performance (Figure 1)? As this thesis has shown, the question will probably never be fully answered as the relative importance of each influencing dimension may vary on an individual level. What can be stated, however, is that one or a few physiological test variables will not discriminate between skiers once they have reached a certain level of performance. Skiers with similar physiological characteristics can reach different competitive performance levels, and vice versa. Alternatively, physiological variables not measured by us, or other research groups, are the ones of importance. Regardless, there is an imminent risk that the use of inappropriate statistical methods may have misled research focus and that the importance of certain physiological qualities for skiing performance may be overemphasized.

Despite extensive physiological testing, included test results could not generate models valid for prediction of competitive performance. Rather, our results indicate that the importance of the physiological dimension is likely due to variations on an individual level. Thus, it can be concluded that the relative
importance of all influencing dimensions must be considered when investigating the sport-specific performance of athletes (Figure 1).

**Is there an assumption of validity?**

With the previous section in mind, another interesting question is, therefore, why the physiological dimension seems to get so much attention from coaches and ski federations alike? One explanation is probably that physiological test results are often easier for coaches to understand in comparison to results provided by tests of other essential qualities (e.g., mental "performance"). For example, the results of a jump test performed on an infrared jump mat are likely easier to interpret and evaluate compared to the assessment and evaluation of reaction time and decision making in the virtual reality [117]. Furthermore, assessment of social skills can be an overwhelming task as this includes measurements of verbal and non-verbal interactions, as well as communications with others in a specific context. Most likely more difficult to comprehend than results from a body mass assessment using a regular body weight scale [81]. **Content validity** [83] may also (incorrectly) be assumed [109] due to the fact that people are generally inclined to accept arguments that support their knowledge and beliefs. To understand the world around them, people tend to simplify complex problems [50]. Because performance in alpine skiing can be difficult to quantify, coaches and leaders may be convinced that selected parts of the physiological dimension are crucial for competitive performance [109]. It is, therefore, reasonable to believe that some of these coaches and leaders may seek evidence to support their presumptions. Another plausible explanation may be that many coaches and leaders assume scientifically reported results to be valid and reliable, as this is the very core tasks of science [120]. However, in the field of alpine skiing research, it seems almost as if the scientific community itself may have contributed to creating some misconceptions regarding the importance of certain physiological qualities for skiing performance. This, in turn, seems to have created a form of chain reaction where coaches and leaders trust what researchers say, and vice versa [109]. The importance of applying correct scientific methods, study designs and statistical analyses when reporting results emphasize the responsibility researchers have towards society [120].

**Validity and reliability of physiological tests in alpine skiing**

During the last decade, physiological testing of athletes has become an essential part of high-performance sports [139]. Due to the often dynamic and complex nature of sport [22,31], a controlled simulation and estimation of athletic performance can provide competitive advantages [17]. Among the many benefits of conducting physiological tests is the opportunity to establish baseline values that provide athletes with an insight into their current physiological status (data
useful when conducting comparative follow-up tests) [28]. Physiological tests can also provide incentives for athletes to try to beat previous test records, providing motivation in their preparatory training [158]. Testing athletes' physiological capacity is important also when designing exercise programs for maximized training efficiency by addressing correct physiological qualities [22]. Finally, test results are used by coaches and managers as selection criteria for recruitment to teams and participation in competition.

To generate useful results within a competitive context, a performance test protocol must be valid and reliable to the performance in question [31]. For the athletes themselves, the validity and reliability of the testing protocol are critical as they presumably perform physiological tests with the intention of identifying strengths and weaknesses in relation to their sport. In sports performance research, different types of validity and reliability can be applied [31]. In general, validity refers to which degree a test protocol or instrument measures what they intend to measure [61] whereas reliability refers to the extent to which they provide consistent results [6]. For physiological test protocols, validity can be divided into three main categories: logical validity, construct validity and criterion validity [31]. Logical validity can be defined as a subjective assessment of whether the test measures what it intends to measure [147]. Construct validity refers to the degree to which the test protocol measures the theoretical construct or the characteristics that are examined (e.g., a comparison between two groups in terms of physiological performance) [147]. Lastly, criterion validity indicates to which degree a test protocol correlates with a present or a prospective external criterion [31,147]. Hence, for alpine skiing, criterion validity refers to the extent to which a test protocol can simulate or predict sport-specific performance.

Based on our results, however, it is unlikely that a performance test protocol for alpine skiers, applied on a group level, will ever achieve high logical, construct or criterion validity for several reasons. In the case of logical validity, high validity applies only if the logical argument is true [147]. As discussed above, several previous studies have found a significant correlation between physiological test results and points or ranking [3,32,55,77,93,94,97,103,127,152,162]. If these results had high logical validity, this would have meant that, for example, athletes with the highest VO₂ value should also be the fastest skiers. However, as our results show, it is relatively unlikely that this argument would be true.

To exemplify the issue with construct validity, an example with basketball players follows. As in other sports, an assessment of the physiological characteristics of alpine skiers may be necessary in order to recognize trend patterns in a specific population, establish normative data, and provide educational content to coaches and others involved in the development of young athletes [22,139]. While this certainly can be important on an organizational level, our results indicate that
descriptive and normative data often are of little use to the very elite athlete. For example, in a sport like basketball, athletes have a competitive advantage of being tall [104]. For a professional basketball team, this is probably vital information when they are about to add new players to their roster. For shorter basketball players, this can be valuable information because they know that they must "train themselves longer" to compete on the same terms as taller players. For NBA players, however, this is probably not important information because they are already playing at the highest level in their sport, where body size is no longer a discriminating factor in terms of performance [104]. Although the basketball-case may be an absurd example, our results indicate that this analogy most likely also applies to elite alpine skiers, where physiological performance comparisons with lower ranked athletes do not help top athletes improve their sport-specific performance. This is especially evident when it comes to VO2peak, where the senior elite athletes in Paper II-III exhibited similar values as the junior elite skiers in Paper I.

Finally, in terms of criterion validity, skiing performance does not seem to be predictable on a group level, at least not using physiological test results alone. As already discussed, this can be due to the fact that several different dimensions (Figure 1) influence competitive skiing performance [46,134,149] and that the relative importance of these dimensions may vary on an individual level. Most likely, this is also due to the lack of a reliable outcome variable [6,31] as FIS points have a considerable within-group variation between seasons (Figure 9). Because of these considerations, it is highly unlikely that a physiological test protocol intended for alpine skiers, applied on a group level, will ever achieve high criterion validity (i.e., high cross-validated Q2) for true racing performance. As such, all these arguments also emphasize the need for a new approach when it comes to assessing and evaluating the physiological performance of elite athletes.

**Methodological considerations**

**Other dimensions**
Because this thesis has focused on the physiological dimension, the importance of other influencing dimensions for alpine skiing performance has not been investigated. Given the fact that competitive performance in alpine skiing is affected by dimensions other than just the physical (such as equipment, skiing technique, and mental performance), the relative importance of these dimensions could also be important to investigate. By including other dimensions, the predictive power for competitive performance on a group level would maybe have been improved.
**Menstrual cycle effects**
The menstrual cycle phases and fluctuations of hormones may affect trainability [156] and physiological performance in women [69]. This may, in turn, explain part of the individual variations in physiological performance between different test occasions (Figure 10). As physical testing occurred in random orders for several years, systematic errors in data were avoided. Implementation of tests based on the menstrual cycle may prove difficult, as the cycle does not always start on the same day and vary in length [69]. Regardless, it was beyond our control when tests were carried out.

**Other predictive modeling procedures**
Besides using only PCA and OPLS, it would also be interesting to investigate the predictive power of physiological test results for competitive performance using other predictive modeling procedures. While we are confident that the analytical techniques used in this thesis are useful in this type of context [87], other predictive methods could have been used to ensure the validity of our results.

**More tests specifically designed for alpine skiers**
This thesis could also be criticized for not including sufficiently challenging and specifically designed tests for alpine skiers. Examples of these could be a more demanding balance test performed in ski boots, a test for the assessment of isometric and eccentric muscle strength as well as specific core strength and core stability tests. While this would have been desirable, it could be argued that valid tests for assessing the sport-specific performance of alpine skiers do not exist. Instead of examining the validity of numerous individual tests for skiing performance, we focused on investigating the predictive power of already validated tests or those previously used in research on alpine skiers. In addition, as the end goal of this doctoral thesis was to provide practically useful results, we mainly chose to include physiological performance tests that can be performed without access to advanced laboratory equipment.

**Fédération Internationale de Ski points**
As mentioned, one of the limitations of this thesis was also the use of FIS points as an indication of competitive performance. While other skiing performance metrics could have been used, FIS points still seem to be the best indication for actual competitive performance over several competition seasons. Still, a more reliable measure of performance had been desirable, which can hopefully be determined in future research.
The novel approach of this thesis

Elite performance in any sport is multi-dimensional [71]. Consequently, data analysis must follow the same trait. Traditionally, variables are analyzed one by one, using bivariate statistical methods [125]. Finding correlations between capacities and performance may not correspond to high predictive power. That is, a correlated variable may or may not be essential for competitive performance. This thesis explores, for the first time in an elite athletic setting, a novel approach of multivariate analysis proven useful among firefighters [86]. By doing so, both correlation and importance of each included physiological testing result are evaluated. A move from evaluating test results on a group level to individual profiling is suggested. Also, other dimensions presented in Figure 1 must be incorporated in future research in order to cover the complex aspects of athletic performance.

Application in sports

Although no valid physiological tests for competitive performance were identified, the results of this thesis can hopefully encourage both athletes and coaches involved in alpine skiing to continue with the implementation of physiological tests. However, as our results show, these tests should be implemented over time with the intention of identifying important physiological qualities for sport-specific performance on an individual level. A test battery intended for alpine skiers should include valid and reliable tests aimed at assessing physiological performance in general (e.g., strength, endurance, mobility and balance) and providing easy-to-understand and practically useful results to training advisors and athletes alike. This in order to provide with a comprehensive individual physiological profile that can be correlated with sport-specific performance (e.g., FIS points) while simultaneously providing with results that can be implemented (and be useful) in everyday training. Furthermore, the results and analytical procedures presented in this thesis can also be useful in sports such as ski cross, snowboard and cross-country skiing where competitive performance is quantified using a similar ranking system such as the one used in alpine skiing. Besides the similarities between the ranking systems, it is also likely that the competitive performance of these athletes, as for alpine skiers, is affected by several interacting dimensions where, for instance, the relative importance of physiological performance varies on an individual level.
Conclusion

A more holistic approach to testing of elite athletes must be considered, as elite performance is multi-dimensional. Before implementing extensive testing of athletes, validity and reliability of protocols applied must be determined. Failing to meet these criteria may have extensive consequence, such as a potential waste of the limited resources for athletes, coaches, clubs, and ski federations as well as misguided training.
Acknowledgments

During my years as a Strength and Conditioning coach at Ski Team Sweden Alpine and as a PhD student, I have met several fantastic people who have all inspired me and, in some way, contributed to the completion of this work. I would like to express my deepest gratitude to the following persons:

My supervisor Christer Malm for everything that you have done for me. Without you I would not have been where I am today and thanks to you, I have gained a more profound knowledge, not only in the field of sports medicine but also about myself. You are an extraordinary researcher but an even better person. Thank you for sharing your expertise with me. I will be grateful for this forever.

My co-supervisor Apostolos Theos because you have always had time to listen and because you have always been there for me. You are a kind-hearted person who always tries to do the best for everyone. Thank you for sharing your knowledge with me and because you have taught me some of the Greek ways of handling different situations in life.

My co-supervisor Ann-Sofie Lindberg because you have contributed structure to this project. You are an incredibly skilled researcher and without you, the completion of this project would have been so much more difficult. Thank you for sharing your knowledge with me and for being such a nice and caring person.

My co-supervisor Richard Ferguson for your invaluable contribution to the completion of this project. Thanks to your involvement and expertise, I have always felt confident that I am on the right track. Thank you for being a part of this project and for sharing your knowledge with me.

The former Sports Director at Ski Team Sweden Alpine, Anders Sundqvist, for believing in me and for the opportunity to start this project. I will always be grateful for everything that you have done for me. I am also grateful to survive the colossal ice hockey tackle that you handed out to me during the 2015 World Championship in Vail, USA.

My mentor and friend Tom Pietilä, who have supported and helped me ever since I started my studies at the Section for Sports Medicine. Thanks for all the advice and because you have continued to motivate and encourage me during periods when it sometimes felt tough.

The personnel at the Section for Sports Medicine: Håkan Alfredson, Kajsa Gilenstam, Lars Berglund and Lisbeth Wikström-Frisén for your
encouraging words and invaluable inputs during this work, Michael Svensson for sharing your knowledge with me and for your encouraging words, Lars Göran Fjellborg for your encouraging words and because you have adjusted my back now and then, Daniel Jansson, for rewarding discussions and because being an arch-enemy during important games between Sweden and Finland in all major international ice hockey tournaments, Ewa Johansson, Britt-Marie Eliasson and Jonas Lorentzon for help with all the administrative and technical work, Ji-Guo Yu for encouraging words.

The personnel at the Sports Medicine Laboratory at Umeå University: Roger Andersson, Lennart Burlin, Mikael Therell and Joel Sjölander for invaluable help during the data collection and all the pleasant conversations in between. Without your help, this project could not have been completed.

My former PhD student colleagues, Andreas Hult, Jonas Johansson, and Tommy Henriksson because you have shown me that “this” can be done and thereby inspired me to continue to work hard.

My friends and former colleagues at Ski Team Sweden Alpine, Anders Nilsson, Sara Königsson and Mikael Junglind, for all the pleasant and rewarding conversations. Thank you for believing in me.

The former head of the Swedish female alpine skiing national team, Fredrik Steinwall, for giving me the opportunity to work with such an incredible group of formidable athletes and colleagues.

All the fantastic athletes I have had the privilege to work with. You are the biggest reason why this project was started. You all have been a huge inspiration during all these years. Thanks for all the wonderful memories, I will carry them with me for the rest of my life.

In addition, I would like to express my deepest gratitude to my family:

My sister Josefine Nilsson and her wonderful family for their love and support. You are all fantastic and I wish that we could meet each other more often.

My fiancé Ida Johansson because you have always been there for me. Without you, I would never have been able to complete this project. Now I finally have some more time to help you with all your crazy ideas. I love you.

Finally, my parents Bo Nilsson and Birgitta Nilsson who have always supported and believed in me. I could not have wished for better parents than you. I am proud to be your son. I love you.
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