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Sammendrag

Kombinert er en tradisjonell vintersport som har vært en Olympisk gren siden de første Olympiske leker fant sted i Chamonix, 1924. I kombinert konkurreres det først i skihopping før en jaktstart i langrenn med bruk av skøyteknikk. For å lykkes er derfor utøverne nødt til å mestre den teknisk utfordrende øvelsen ved et skihopp hvor vertikal kraftimpuls på hoppkanten og kroppsmasse er viktige karakteristikker, i tillegg til den påfølgende 10-km langrennskonkurransen som krever en høy aerob utholdenhet og overkroppskapasitet for effektiv stavbruk. Innsikt i de spesifikke fysiske kravene, fysiologiske og tekniske kapasitetene, og treningskarakteristikker av kombinertløpere i verdensklasse er derimot en mangelvare. Hovedmålet med denne avhandlingen var derfor å definere de viktigste faktorene for prestasjon i kombinert, de tilhørende fysiologiske og biomekaniske kapasiteter målt i testlaboratorium av betydning for kombinertprestasjon, og treningskarakteristikker som kreves av kombinertløpere for å nå et verdensklassenivå.

Totalt 27 verdenscuputøvere deltok frivillig i de fire studiene som er inkludert i denne avhandlingen. *Studie I* undersøkte betydningen av idrettsspesifikke kapasiteter målt i laboratorium for henholdsvis hopp-, langrenn-, og totalprestasjonen i et verdenscuprenn i kombinert. *Studie II* sammenlignet idrettsspesifikke kapasiteter i laboratorium og årlig trening hos verdensklasseløpere i kombinert med spesialister i hopp og langrenn. *Studie III-IV* ga en detaljert beskrivelse av treningsperiodiseringen til kombinertløpere i verdensklasse i de ulike treningsfasene av en sesong og over flere sesonger.

Hovedfunnene var som følgende; (1) vertikal hastighet i imitasjonshopp og kroppsmasse var i par best egnet til å predikere hopprestasjon, mens VO_{2peak} på rulleski normalisert for kroppsmasse og effekt i staking var best egnet til å predikere langrennsprestasjon blant kombinertløpere; (2) kombinertløpere på verdensklassenivå avvek 10-17% i ulike kapasiteter målt i laboratorium sammenlignet med hopp- og langrennsspesialister, og gjennomførte henholdsvis halvparten av hoppspesifikke økter og to tredjedeler av utholdenhetstimene; (3) kombinertløpere i verdensklasse gjennomførte ~850 årlige treningstimer i deres mest vellykkete sesonger, hvor mer enn 60% av dette var utholdenhetstimer. Mens treningsfrekvensen var relativt stabil gjennom sesongen så ble det totale treningsvolumet gradvis redusert fra den generelle forberedelsesperioden til konkurranseperioden. For både utholdenhet og hoppspesifikk trening fulgte treningsmønstrene spesifisitetsprinsippet, med mer generell trening i de første treningsperiodene etterfulgt av mer konkurranselik trening i konkurranseperioden; (4) detaljert analyse av en Olympisk mester i

kombinert viste en progressiv økning av utholdenhetstrening over de tre første sesongene av en fire år lang OL-syklus, før årlig utholdenhetstrening ble redusert med 12% i OL-sesongen. Utøveren vedlikeholdt generell vertikal hoppkapasitet på ~3 $m \cdot s^{-1}$ gjennom syklusen, til tross for en økning av 7 kg i kroppsmasse, mens vertikal hastighet i skihoppspesifikk satsbevegelse økte med 14% og absolutt VO_{2peak} på rulleski med 19%. Disse endringene sammenfalt med en nær dobling av årlige imitasjonshopp og en økning av ~200 timer årlig utholdenhetstrening. Utøveren hadde også et spesifikt fokus på å forbedre avslutningsegenskaper i langrenn gjennom hele syklusen, noe som ble en avgjørende faktor da begge OL-gullene ble vunnet i spurtoppgjør.

Denne avhandlingen viser hvordan kombinertløpere i verdensklasse oppnår fysiske kapasiteter tett opptil det maksimale av menneskelig potensial både i skihopp og langrenn ved å gjennomføre samtidig trening av styrke og utholdenhet for å optimalisere kombinertprestasjon. Kombinertutøvere i verdensklasse balanserer 800-1000 årlige treningstimer med to tredjedeler i favør av utholdenhetstrening og én tredjedel hoppspesifikk trening (dvs. trening i hoppbakken, teknikktrening, styrke, koordinasjon og bevegelighetstrening). Treningen for henholdsvis hopp- og langrennsprestasjon gjennomføres med en tilsvarende fordelingsmodell som spesialistene i hopp og langrenn bruker. Kombinertløperne gjennomfører derimot i gjennomsnitt kortere økter. Lavintensitets-utholdenhetstrening var hovedfaktoren for justering av totalt treningsvolum, mens mengde hoppspesifikk trening og høyintensitets-utholdenhetstrening var vedlikeholdt på et stabilt nivå både over sesonger og treningsfaser innad i sesong. Analysene av en dobbel-Olympisk mester i kombinert indikerer at det kan være hensiktsmessig å fokusere på å øke muskelstyrke og vertikal kraftimpuls i underkroppen i ungdomsårene når mengde utholdenhetstrening er lav. Deretter bør en gradvis øke fokus på å utnytte den opparbeidede kapasiteten i den mer teknisk krevende satsbevegelsen i et skihopp i senioralder da mengde utholdenhetstrening nødvendigvis må økes for å heve langrennsprestasjonen ytterligere.

Ovennevnte avhandling er funnet verdig til å forsvares offentlig
for graden Doctor Philosophiae
Disputas finner sted i Auditoriet MTA, Medisinsk Teknisk Forskningssenter
Mandag 13. mai 2019, kl. 12:15

Summary

Nordic combined (NC) is a traditional winter sport that has been part of the Olympic program since the first Winter Games in Chamonix, 1924. In NC, a ski jumping (SJ) event is followed by a pursuit cross-country (XC) skiing race employing the skating technique. For successful NC performance, the athletes therefore have to solve the technical challenging task of a ski jump where the vertical impulse at the take-off and low body mass are important characteristics, as well as the subsequent 10-km XC skiing race requiring a high aerobic and upper-body power capacity. However, knowledge about the physical demands, physiological and technical capacities, and the training characteristics of world class NC athletes is lacking. Therefore, the main purpose of this thesis was to elucidate the factors important for performance in NC, as well as the corresponding laboratory capacities and training characteristics required by NC athletes for reaching a world class level.

A total of 27 World Cup athletes volunteered to participate in the four studies included in this thesis. *Study I* investigated the associations between sport-specific laboratory capacities and SJ, XC skiing, and overall NC performance in a World Cup NC event. *Study II* compared sport-specific laboratory capacities and the annual training of world class NC athletes with specialized ski jumpers and XC skiers. *Study III-IV* described the annual and long-term training periodization of world class NC athletes.

The main findings were as follows: (1) vertical velocity obtained in imitation jump and body mass provided the best prediction of SJ performance, whereas body mass normalized VO_{2peak} obtained in XC roller ski skating and double poling power provided the best prediction of XC performance in NC athletes; (2) world class NC athletes differed by only 10-17% in various laboratory capacities and performed half the number of SJ specific sessions and two-thirds of the endurance training hours as SJ and XC specialists, respectively; (3) world class NC athletes performed ~850 annual training hours in their most successful season with more than 60% of these being endurance training. Although training frequency was relatively constant throughout the season, the total training volume was gradually reduced from the general preparation phase to the competition phase. For both endurance and SJ specific training, the training patterns logically follow the principle of specificity, with more general training in the initial training periods, followed by more competition-specific loading towards and in the competition phase; (4) detailed analyses of an Olympic NC Champion showed a progressive increase of endurance training over the three initial seasons of a four-year Olympic cycle, before a 12% reduction of endurance training in the Olympic season. The athlete maintained his

general vertical jump capacity at ~3 $m \cdot s^{-1}$ throughout these years, despite an increase of 7 kg overall body mass, while improving his vertical jump velocity of sport-specific imitation jumps by 14% and his absolute VO_{2peak} on roller-skis with 19%. These changes coincided with an almost twofold increase of annual imitation jumps and an increase of ~200 annual endurance training hours. An emphasis on improving finish-sprint ability in XC skiing was present in all seasons, a determining factor since both Olympic gold medals were won in the final sprint.

This thesis demonstrates how world class NC athletes achieve physical capacities close to the maximum human potential both in SJ and XC skiing when conducting concurrent strength/power and endurance training to optimize their NC performance. In this context, world class NC athletes balance the overall 800-1000 annual training hours as two-thirds of endurance and one-third SJ specific training (i.e. ski jumps, dry land technique training, strength/power, motor control, and stretching). The training for SJ and XC performance is performed using a similar distribution model to that of specialized SJ and XC skiers. However, NC athletes performed on average shorter session durations compared to the specialists. Low-intensity endurance training was found to be the main manipulator of overall training volume for reaching the world class level in NC, whereas the amount of SJ specific training and high-intensity endurance training was maintained relatively stable across seasons and season training phases. Furthermore, our data from a multiple Olympic NC Champion indicate that it is advisable to focus on increasing lower-body muscle strength and vertical jump impulse in youth years, followed by increased emphasis on utilizing the acquired capacity in the more technical execution of the take-off movement in the senior years when it is necessary to increase the volume of endurance training to further enhance XC skiing capacity.

List of publications

This thesis is based on four original studies, which are referred to by their roman numbers throughout the thesis. The thesis presents a selection of the results in these papers and also includes supplementary data.

Study I Rasdal V, Fudel R, Kocbach J, Moen F, Ettema G, Sandbakk Ø (2017) Association between laboratory capacities and world-cup performance in Nordic combined. PLoS One 12(6), e0180388. Doi: 10.1371/journal.pone.0180388

Study II Sandbakk Ø, Rasdal V, Bråten S, Moen F, Ettema G (2016) How do World-Class Nordic Combined Athletes Differ From Specialized Cross-Country Skiers and Ski Jumpers in Sport-Specific Capacity and Training Characteristics? Int J Sports Physiol Perform 11(7), 899-906. Doi: 10.1123/ijspp.2015-0285

Study III Tønnessen E, Rasdal V, Svendsen IS, Haugen TA, Hem E, Sandbakk Ø (2016) Concurrent Development of Endurance Capacity and Explosiveness: Training Characteristics of World-Class Nordic-Combined Athletes. Int J Sports Physiol Perform 11(5), 643-654. Doi: 10.1123/ijspp.2015-0309.

Study IV Rasdal V, Moen F, Sandbakk Ø (2018) The Long-Term Development of Training, Technical, and Physiological Characteristics of an Olympic Champion in Nordic Combined. Front Physiol 9, 931. Doi: 10.3389/fphys.2018.00931

Supplementary data (unpublished)

The contribution from ski jumping and cross-country skiing performance on overall Nordic combined performance level in individual World Cup events between 2008-09 and 2017-18.

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Being born and raised at the western coast of Norway with hardly any snow throughout the year, my experience with winter sports was for the longest time non-existing. I could therefore never have foreseen to be granted the trust and opportunity to work on a daily basis with some of the world's best Nordic combined athletes through employment in the National Ski Federation and Olympiatoppen. The learning curve has been steep, and the simultaneous work on this thesis at NTNU SenTIF has been paramount to guide me towards the important questions and not get lost in the infinity of uncertainty in an underexplored scientific field of Nordic combined. With lack of experience and a childlike curiosity, I would have taken many wrong turns on this path if it had not been for the amazingly talented and caring people supporting and guiding me along the way. I want to express my sincere gratitude, to those of you mentioned, and those of you not, for sharing your knowledge, guidance, friendship and positive energy throughout these years. I would especially like to thank…

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Finally, my wife Stine. Simply for being you, and for our magical son Elias that truly gives perspective on what is important in life.

Table of Contents

Abbreviations

$[La^-]_b$	Blood lactate concentration
BMI	Body mass index
CMJ	Countermovement jump
CP	Competition phase of the season (January-March)
GE	Gross efficiency
GP	General preparation phase of the season (June-October)
HIT	High-intensity training
HR	Heart rate
HS	Hill size of the jumping hill
IMIT	Sport-specific imitation jump of a ski jump on dry land
K-point	Construction point of the jumping hill
LIT	Low-intensity training
MIT	Moderate-intensity training
NC	Nordic combined
RER	Respiratory exchange ratio
RP	Regeneration phase of the season (April)
SJ	Ski jumping
SP	Specific preparation phase of the season (November-December)
SQJ	Squat jump
TP	Transition phase of the season (May)
V_h	Horizontal velocity
V_v	Vertical velocity
VO_{2peak}	Peak oxygen uptake
XC	Cross-country

INTRODUCTION

Olympic Nordic skiing originates from the Nordic countries and consists of the winter sport disciplines ski jumping (SJ), cross-country (XC) skiing, and Nordic combined (NC) as the combination of both SJ and XC skiing. While the original use of XC skiing for transport and travel over snow has been traced back thousands of years, the first recorded evidence of SJ is much more recent with Olaf Rye, a Norwegian military lieutenant, jumping 9.5 meters in 1808 to motivate troops with his bravery (Gotaas 2011). XC skiing has throughout history been an important skill to master in the Nordic militaries, and Norwegian regiments routinely organized skiing contests with prizes in the 19th century to enhance the interest in developing skiing skills (Gotaas 2011).

The practice of XC skiing for sport was also strong in the Norwegian community, and in 1843 the world's first official XC competition was arranged in Tromsø, Norway. Only two decades later, civilians started competing in winter carnivals in Norway where all participants competed in both SJ and XC skiing, with the results from both competitions added to crown the ultimate winter sport athlete as the NC winner. NC was also the main event in the first major tournament held in Nordic skiing, the Holmenkollen Ski Festival in 1892.

All disciplines of Nordic skiing have been Olympic events since the first Winter Olympics was arranged in Chamonix, France, in 1924. Originally, it was the norm for athletes to compete in both SJ and XC skiing, where the results from the 18-km XC race were converted and added together with the SJ results to declare the overall NC winner. Hence, it was not uncommon in the first Winter Olympics for athletes to win medals in several disciplines. In the first Olympics of 1924, for instance, Torlauf Haug won gold in both XC skiing (18-km and 50-km) and NC as well as bronze in the SJ competition (he was degraded to fourth 50 years later, after a scoring computational error was discovered). A call for specialization of the disciplines grew, however, and from the 1932 Olympics a second SJ event was included exclusively for NC athletes, before an exclusive XC race was also held in the 1956 Olympics.

Competition formats of NC in the Olympics have varied greatly over the years (see Figure 1), but in general the results from one type of competition have always been converted and taken with the athletes into the other to determine the overall winner. Until the 1952 Olympics the XC race was performed first, followed by the SJ competition a few days later.

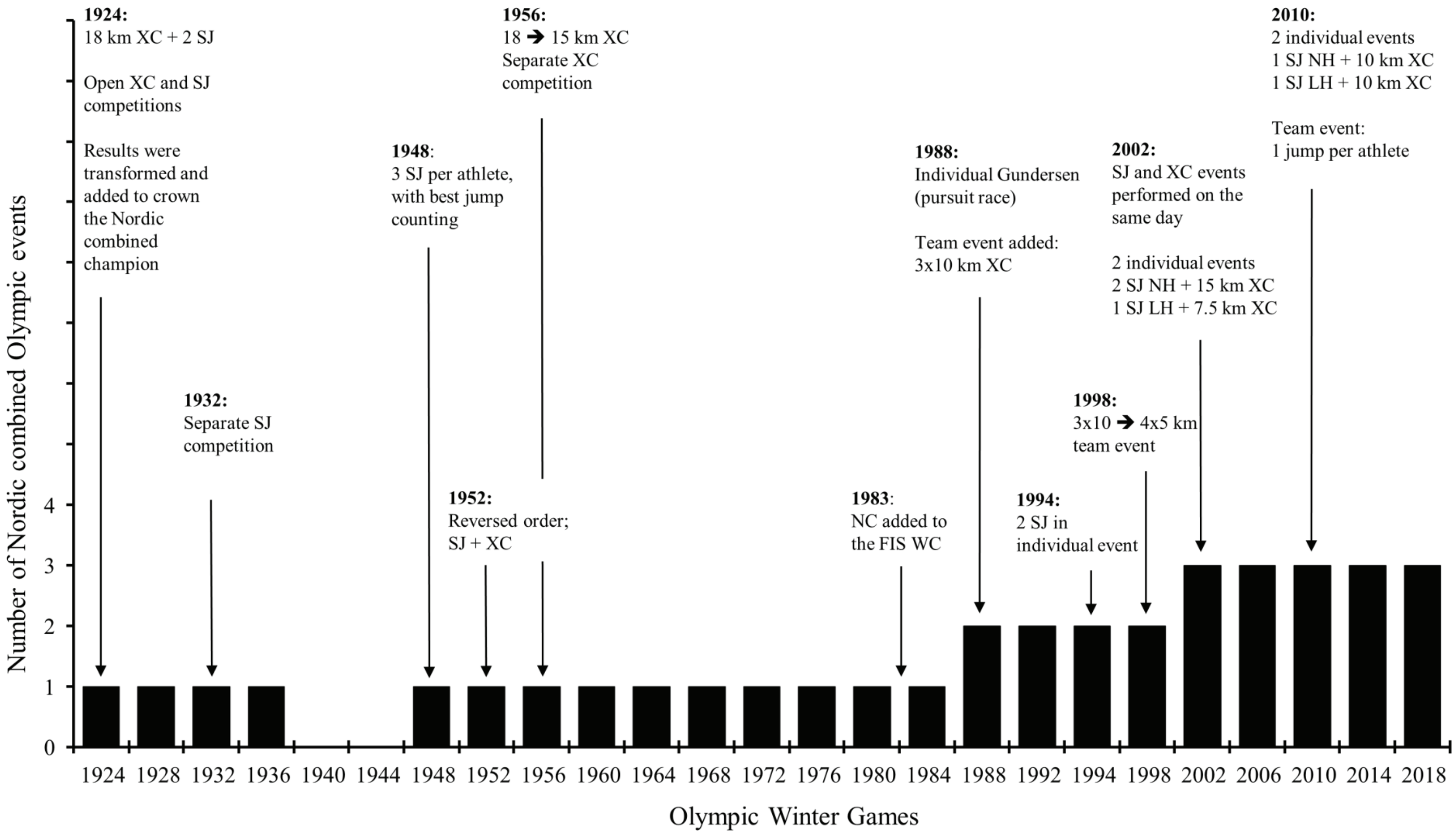


Figure 1. Timeline of changes in competition format for Nordic combined in the winter Olympics from 1924 to 2018.
XC; cross-country, SJ; ski jump, NC; Nordic combined, NH; normal-hill event, LH; large-hill event, WC; World Cup
(Source: OlyMADMen, 2018)

With the time difference between athletes from the XC race becoming too large to counter in the SJ competition, the order of events was turned from the 1952 Olympics before also the distance of the XC race was reduced from 18 to 15-km in the subsequent 1956 Olympics (OlyMADMen 2018).

The most significant change in the competition format was the introduction of the Gundersen Method in the 1988 Olympics. The XC race was then performed as a pursuit race (rather than interval start), ordered and timed according to the results in the SJ competition where only the top 50 athletes were allowed to start the XC race. Consequently, the leader after the SJ would be first to start skiing, and the first athlete to cross the finish line was the winner. This made the event more understandable and interesting for the general spectator, and many of the calculation regulations since have been aimed towards balancing the relative contribution of the two events for the overall result, and thus collect as many athletes in the field as possible towards the end of the XC race for a final sprint. 1988 was also the year when the XC skating technique was used for the first time in the Olympics, and has been used in all NC competitions since.

To enable a second individual event to take place in the 2002 Olympics, the order of the SJ and XC competitions was changed to be performed on the same day. Since 2010, both individual events have been performed with a single SJ either in a normal or large hill (see Table 1) followed by a 10-km XC pursuit race a few hours later.

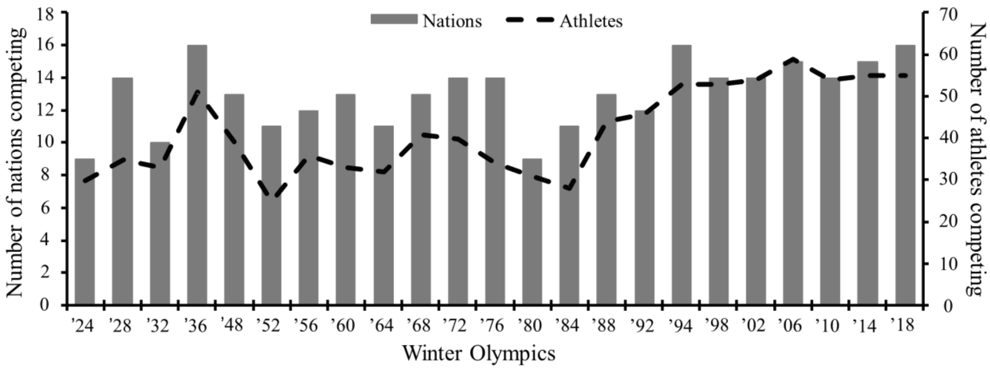


Figure 2. Number of nations and athletes participating in Nordic combined in the Winter Olympics from 1924 to 2018 (Source: www.olympic.org).

Physiological demands of Nordic combined

Searching for “Nordic combined” in the search engines SPORTDiscuss and PubMed results in a total of 41 articles published by November 2018 either about NC as a sport or using NC athletes as subjects. Nearly half of the studies are related to health/safety, and none provide any information on the specific demands for NC athletes. Of laboratory capacities, Pääsuke et al. (2001) measured greater isometric strength and rate of force development in well-trained Estonian NC athletes compared to untrained subjects, and Rønnestad et al. (2012) measured a mean one-repetition-maximum of ~100 kg in deep squats in Norwegian NC athletes combined with an aerobic capacity (VO_{2peak}) on roller-ski skating of ~66 $ml \cdot kg^{-1} \cdot min^{-1}$. Angermann et al. (2006) obtained cycling and double-poling VO_{2peak} among Swiss NC of respectively 57.3 ± 3.7 and 53.6 ± 4.2 $ml \cdot kg^{-1} \cdot min^{-1}$. However, the majority of athletes investigated in these studies can not be considered world class, thus their capacities do not represent the physical demands for elite performance.

In more recent literature, Tønnessen et al. (2015a) has reported VO_{2max} values of Norwegian Olympic athletes in a broad range of endurance winter sport disciplines. Here, world class NC athletes were assessed with a mean VO_{2max} of 77 $ml \cdot kg^{-1} \cdot min^{-1}$, whereas world class XC distance and sprint skiers showed 84 and 78 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. The NC athletes investigated had also a lower body mass than the male XC skiers, which creates a greater group difference when investigating the absolute VO_{2max} values; i.e. 5.3 $L \cdot min^{-1}$ in NC and 6.4 and 6.3 $L \cdot min^{-1}$ in XC distance and sprint skiers, respectively. Schmitt et al. (2018) found lower VO_{2max} values in the French national team athletes, but the 5% difference between NC athletes (66.1 ± 3.2 $ml \cdot kg^{-1} \cdot min^{-1}$) and male XC skiers (69.3 ± 3.6 $ml \cdot kg^{-1} \cdot min^{-1}$) was similar to the Norwegian skiers in the study by Tønnessen et al. (2015a).

Literature describing the physical demands, capacities, and training of world class NC athletes is sparse. Considerably more literature exist, however, on the demands of SJ and XC skiing. The reported demands from studies on world class SJ and XC skiing specialists may provide a well-suited starting point for elucidating the demands also in NC.

Ski jumping

A SJ hill is located on a steep slope, consisting of the in-run, take-off table, and a landing hill (see Figure 3). The construction point (K-point) of a hill serves as a “target” of how far the competitors can safely travel in the air, while the classification of the hill is based on the maximum jump length the hill is designed for (i.e. hill-size (HS), see Table 1). Most senior international NC events, including the Olympics, are performed at HS95-HS109 (i.e. normal hill) and HS130-HS145 meter hills (i.e. large hill).

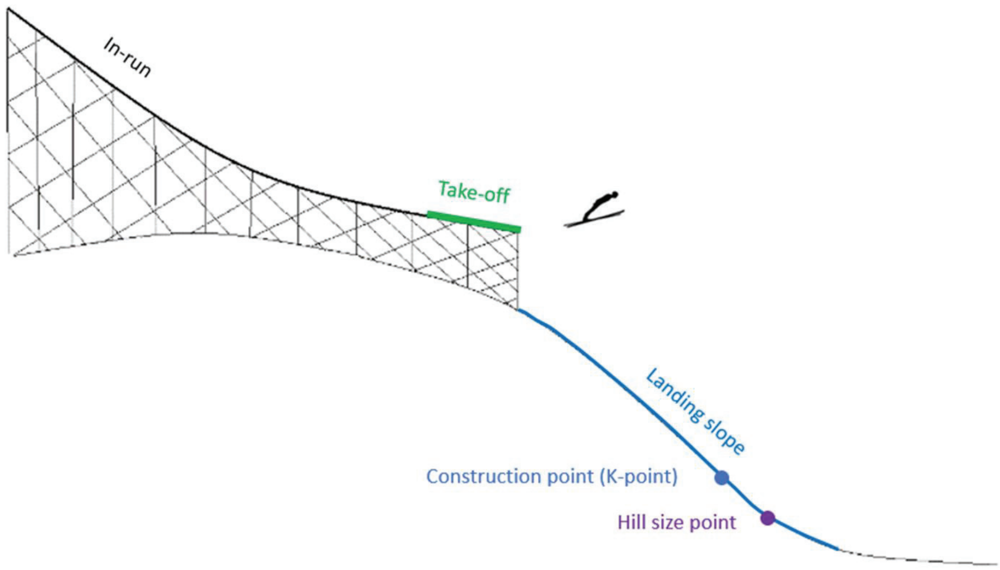


Figure 3. Illustration of a ski jumping hill, with the in-run, take-off table, and a landing slope with a defined construction point and hill size.

The ski jump itself is commonly divided into six phases; in-run, take-off, transition to flight, flight, preparation for landing, and landing (Schwameder 2008). The overall aim of the athlete before the flight phase is to leave the ramp with as high horizontal (v_h) and vertical (v_v) velocity as possible. Thus, starting the jump, the athlete tries to minimize both the friction between skis and snow and the aerodynamic drag in order to maximize in-run speed and thus v_h. As a consequence of the curved form of the in-run just before the take-off ramp (i.e. the *radius*), the athlete has to generate a centripetal force up to 1.6 G immediately before starting the take-off motion (Ettema et al. 2005). With limited time available after the radius [~0.35 seconds (Müller 2009)], the athlete aims to create v_v perpendicular to the ramp by use of muscular forces. Simultaneously as creating v_v the athlete also has to produce the appropriate amount of forward angular momentum in order to obtain an advantageous angle between body and skis as soon as possible after leaving the ramp. If the forward angular momentum is too low, a disadvantageous flight position reduces v_h and consequently results in poor competitive performance. Worse is the production of too much forward angular momentum as this substantially increases the risk of tumbling forward (Müller 2009).

During the flight, the gravitational force, the lift force, and the drag force act upon the athlete. While the athlete´s posture, flight technique, and equipment can strongly influence the aerodynamic forces (lift and drag force) (Jung et al. 2014; Lee et al. 2012), the take-off motion is widely considered as the most significant phase of the ski jump for a successful performance (Arndt et al. 1995; Müller 2009; Schwameder 2008; Virmavirta et al. 2009).

Table 1. Classification of the different jumping hills used in international Nordic combined competitions according to the hill size.

Classification	Olympic events	K-point	Hill size (HS)
Medium hill (MH)		45-74 m	50-84 m
Normal hill (NH)	Nordic combined Ski jumping	75-99 m	85-109 m
Large hill (LH)	Nordic combined Ski jumping	100-169 m	110-184 m
Ski flying hill		≥ 170 m	≥ 185 m

SJ performance is not exclusively determined by the jumping distance. Competitors are ranked according to a numerical score obtained by adding up components based on style, in-run length (i.e. gate), and wind conditions in addition to distance. For normal and large hills, which are the two hills used for Olympic events in NC, the athletes are awarded 60 points if they land on the K-point, and points are added or deducted for every meter they jump further or shorter respectively. A maximum of 60 points may be added to the score based on the style of the jump, which is based on “the aspect of precision (timing), perfection (carrying out of the movements), stability (flight-position, outrun) and general impression” (FIS 2018b).

Gate and wind factors were introduced in the World Cup in 2009, but not in the Olympics until 2014. This was done in an effort to allow fairer comparison of results for variable outdoor conditions. Ideally, all athletes in a single competition jump from the same gate. If the wind conditions change too much during the competition, however, the judges have authority to adjust the in-run length – and thus in-run speed – to provide safe and fair competitions. If doing so, a gate factor will be added or subtracted depending on whether the athletes receive less or more in-run length. Based on data from several wind sensors positioned in strategic positions on the jumping hill, an advanced calculation determines compensation points for the actual wind conditions at the time of the jump. These points are added or withdrawn depending on the direction of the wind; i.e. when there is tail wind, the points are added, and when there is front wind, the points are subtracted.

Figure 4. The original Holmenkollen ski jumping hill in Oslo, Norway, in 1892 to the left, and the upgraded modern version to the right. (Reprinted from VisitOSLO (www.visitoslo.com))

Until the 1990s, the preferred flight-position of most jumpers was the so-called parallel-style, where the athletes would lean far forward from the ankles with knees straight and skis held parallel and inclined slightly upward (see Figure 5). It was the Swedish jumper Jan Boklöv that pioneered the use of the modern V-style in the 1980s (Müller 2009). Here, the skis were spread outwards in an aerodynamic "V" shape, with the athlete's body lying much flatter between them compared to the parallel-style. This created more surface area for lift force, and instantly improved jumping distances at the same in-run speed (Müller 2009). It also had a favorable effect of granting more stability in the air, allowing the athlete to adjust the airstream on skis and body independently. At first, this new technique was opposed by the judges, who considered anything but the parallel-style to be inappropriate. Consequently, the improved jumping lengths were almost annulled by the poor styling points received. However, after Jan Boklöv insisted on using the technique and ultimately won the overall World Cup season in 1988-89, more jumpers started to follow, and eventually also the judges had to concur. By the mid-1990s the style had become the predominant style of jumping used by all NC and SJ athletes, and recognized as valid by the judges and FIS.

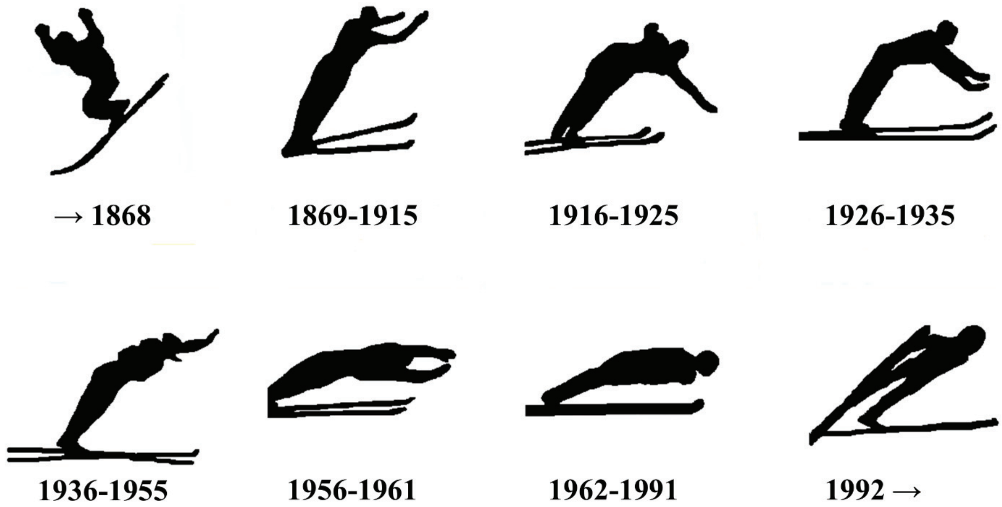


Figure 5. Development of ski jumping techniques from 1868 to the modern V-style technique that mounted in 1992 as the main technique used by World Cup athletes. (Amended from Vodicar & Bost (2017))

Physiological demands of ski jumping

Improvements in the construction of jumping hills, equipment, and technique patterns of athletes have increased the jumping distance immensely over the last century (see Figure 4 and 5 for illustrations). From a record jump of 21.5 meters in the first major competition in the Holmenkollen SJ hill in 1892, the current record jump set in 2011 by Andreas Kofler is 141 meters (see Figure 6). Since 1936, world record jump has increased by 1.9 m per year (Müller 2009) with the current longest jump set by the Austrian jumper Stefan Kraft at 253.5 m in Vikersund, Norway, in 2017.

Biomechanical methods have been applied to study SJ for almost 100 years, with the main research areas being field studies, laboratory studies on simulation jumps, and computer simulations of the flight phase to study the effect of isolated variables such as flight position or body mass (Müller and Schwameder 2003). Field studies have reported results from both the jump as a whole and for the different phases individually. Still, most attention has been granted to the take-off as the phase deemed crucial for the total jump performance (Arndt et al. 1995; Schwameder 2008). When performing field studies, outdoor conditions (e.g. wind, temperature, weather) will naturally affect the results found in different studies, and so will the homogeneity of the study group investigated. There is a current consensus, however, that significant factors for SJ performance is a high v_v from the take-off in combination with generation of angular momentum to acquire a small body-ski angle after 20 m of the flight, and a low body mass (Müller and Schwameder 2003; Müller 2009).

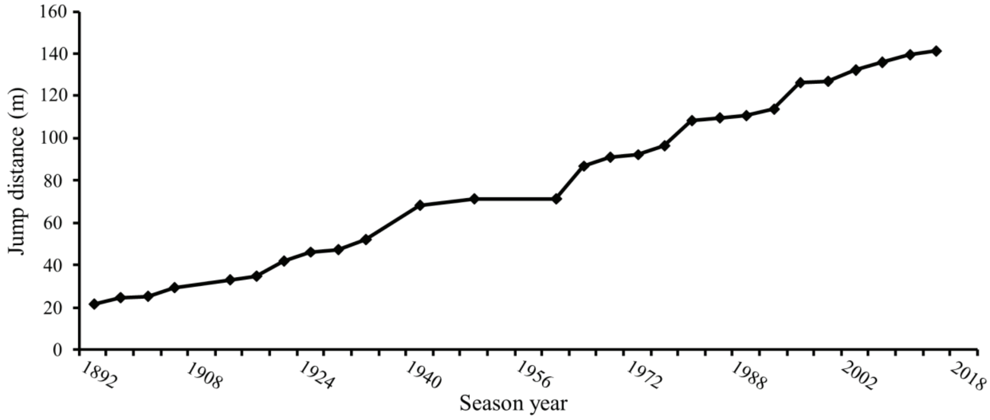


Figure 6. Longest recorded competition jumps in Holmenkollen ski jumping hill in Oslo, Norway, between 1892 and 2018. (Source: Ski jumping hill archive (http://www.skisprungschanzen.com))

With the introduction of the V-style technique in the 1990s, the aerodynamics of the flight phase became more important than before. This development was associated with a 4 unit drop in body mass index (BMI) among elite ski jumpers from ~24 kg·m^{-2} in 1970 to ~20 kg·m^{-2} in 2000 (Müller 2009; Müller et al. 2006). In response, FIS introduced a regulation in 2004 stating that athletes below a BMI of 20.5 would be penalized with a shorter maximum ski length, thus reducing the aerodynamic lift they can achieve and limiting the effect of the lower body mass. This rule was regulated again in 2018, from the athletes being weighted with their jumping equipment to without, and thus the minimum body mass limit was effectively raised. Consequently, a BMI of ~20 has been reported in recent studies in both ski jumpers as well as NC athletes (Janura et al. 2016; Janura et al. 2015).

Laboratory studies on vertical jumps have reported a broad range of jump capacity in ski jumpers, where the discrepancy is likely related to measurement equipment and level of athletes. For instance, Rønnestad (2013) and Janura et al. (2015) reported a 20% difference in squat jump height in ski jumpers of various performance levels (respectively 43 and 53 cm). Similarly, for sport-specific imitation jumps, Virmavirta and Komi (2001) reported a mean maximum vertical velocity of 2.38 m·s^{-1} in Finnish national ski jumpers produced over 0.72 s, whereas Schwameder et al. (1997) reported 3.18 m·s^{-1} produced over 0.35 s in the Austrian national team. The discrepancy in equipment, level of athletes, equipment used, and calculation of end-point results thus make comparisons difficult, and more data are needed before any conclusion on true benchmark values for elite performance may be made.

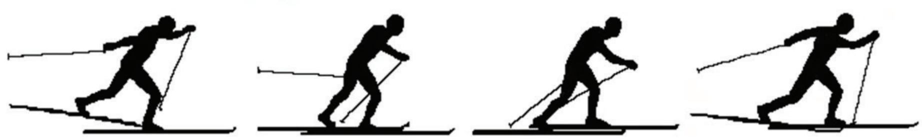
In summary, SJ is a highly complex technical sport, where each phase of the jump is dependent on the success in the previous phase (Schwameder 2008). The athlete has to solve extremely difficult sensorimotor tasks where even small mistakes in one of the crucial phases may reduce the performance dramatically. Consequently, a majority of the ski jumpers' training consists of jumps in different jumping hills and technique training on dry land with variation in the boundary conditions (Ettema et al. 2016; Rønnestad 2013). The production of a high v_v at take-off also requires the ability to produce a high net force impulse in limited time, and consequently physical strength training aimed for this purpose is performed by both SJ and NC athletes throughout the training year (Bösl et al. 2007; Pääsuke et al. 2001; Rønnestad 2013). Unfortunately, due to limited validity in the analyses of strength, power, and technique training, successful training patterns in sports where these components are the primary determinants of performance are not well described in the scientific literature. Anecdotally, however, ski jumpers emphasize heavy strength training with few repetitions to increase their maximal strength with minimal hypertrophy during the general preparation phase of the season, whereas more emphasis is gradually placed on ballistic and high-velocity strength training to develop or maintain peak power output as the season progresses. Currently, there are no studies on how to best combine such delicate technical and physical strength training with high amounts of endurance training.

Cross-country skiing

In the 2008-09 season the main individual World Cup events in NC were changed from 7.5 and 15 km XC races following the large hill and normal hill jumping competition, respectively, to a 10-km XC pursuit race regardless of the size of the hill. In the last three Winter Olympics since then (i.e. Vancouver 2010, Sochi 2014, and PyeongChang 2018) the fastest XC course time in NC has ranged from 22.4 to 24.5 minutes.

Initially, competitive XC skiing for both NC as well as specialist events included only interval-start classical races, where the athletes skied with skis parallel and kicking backward to create a gliding motion across the snow (see Figure 7A). In the 1980s, however, a revolution in international XC skiing resulted in the introduction of a freestyle discipline using the skating style. This technique is more similar to speed skating, where the skier pushes perpendicular to the ski's direction positioned at an outward angle (see Figure 7B), thus creating a zig-zag movement that in contrast to the classical technique enables force production in the gliding phase, thereby generating more speed than with the diagonal stride. The skating technique was not completely new at the time, as ski orienteering and marathon skiers also adopted the style in the 1960s and 1970s, respectively, but it was not until the American skier Bill Koch applied the technique in FIS-sanctioned races to win the 1982 overall World Cup, that other World Cup XC skiers followed (Gotaas 2011). Initially, the XC community was split in its view on the development of the sport. In particular, the Scandinavian countries, with rich skiing tradition using the classical style, were passionate opponents of allowing the XC skating technique to develop. After various efforts to stop skiers from using the variations of the skating technique, FIS eventually had to accept the development, and divided the sport into classical and freestyle events in 1986. NC quickly chose freestyle for their competitions, and the 1988 Winter Olympic Games would be the first Olympics where NC athletes used this technique.

A



B

Figure 7. Illustration of the two cross-country skiing disciplines, displaying the classical technique at the top (**A**) and the skating technique at the bottom (**B**).

All FIS regulated XC races, including the 10-km XC race of NC, are performed in competition courses mandated to include approximately one-third uphill, one-third flat, and one-third downhill (FIS 2018a). The constantly changing incline of the course require skiers to repeatedly switch between different skiing techniques, where the choice of technique is dependent on incline and speed (see Figure 8). With such diversity in competitive demands, the scientific interest in XC skiing has grown from less than 80 publications in the 1980s to more than 200 between 2010-2018.

Physiological demands of cross-country skiing

The aerobically derived proportion of the different distances in XC skiing (i.e. from 70-75% in sprint skiing to 85-95% in longer distances) is comparable to other endurance events of similar race duration (Sandbakk and Holmberg 2014). With the alteration of terrain in XC courses, however, XC skiers will often fluctuate immensely in work rate during the race using work rates considerably higher than that required to elicit VO_{2max} in the uphill terrains, and utilizing the downhill sections for recovery (Sandbakk and Holmberg 2014). Consequently, XC skiers must master a wide range of speed and terrains.

In the skating technique employed by NC athletes, higher speeds within a sub-technique are produced by increasing either cycle length or cycle rate. One important strategy for enhancing cycle length is more effective poling (Sandbakk et al. 2013a; Sandbakk and Holmberg 2014). The importance of upper-body power for XC skiing performance is repeatedly shown in recent literature (Grasaas et al. 2014; Hegge et al. 2015; Stöggl et al. 2010), which adds to the complexity for NC athletes to balance the upper-body muscle-mass and power beneficial for XC skiing performance and its potential negative influence on SJ performance.

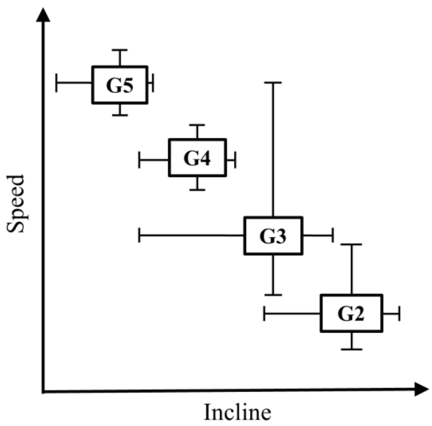


Figure 8. The four main sub-techniques employed in cross-country skating, depending on incline and speed.

Although one-third of the race course is uphill terrain, it constitutes the most performance-differentiating terrain with more than 50% of the total racing time spent in uphill segments (Andersson et al. 2010; Sandbakk et al. 2011a). Accordingly, XC skiers have possessed some of the highest VO_{2max} values ever reported with 80-90 $ml \cdot kg^{-1} \cdot min^{-1}$ among male skiers (Holmberg 2015; Sandbakk and Holmberg 2014; Tønnessen et al. 2015a). While this remarkably high aerobic capacity has not changed much since the 1960s (Saltin and Astrand 1967), the average skiing speed in the classical skiing technique has increased by 20% from the 1968 Grenoble Olympics to the 2014 Sochi Olympics (OlyMADMen 2018). Although we do not know how much of this improvement in performance is due to the athletes' training versus technology and equipment, skiers today engage in more goal-oriented training than previously with more specific roller-ski training in the summer and utilize more sophisticated periodization models (Sandbakk 2017). New race formats have also increased the competitive demands on e.g. anaerobic capacity, upper-body power, and high-speed techniques (Sandbakk and Holmberg 2014), and better skiers have been shown to ski more efficiently and have an ability to produce longer cycle lengths than lower ranked competitors (Bilodeau et al. 1996; Sandbakk et al. 2013b; Sandbakk et al. 2010).

Endurance training is logically the major component of XC skiers' training and accounts for ~95% of their annual 800 training hours, with strength and speed training accounting for the remaining 5% (Sandbakk et al. 2011b; Tønnessen et al. 2014). As in several other endurance sports, world class XC skiers have been described to periodize their annual training according to a polarized intensity model with a high volume (75-90%) of low-intensity training (LIT) and a low volume (10-25%) of high-intensity training (HIT) (Sandbakk and Holmberg 2014; Sandbakk et al. 2011b; Seiler and Kjerland 2006; Seiler 2010; Solli et al. 2017; Tønnessen et al. 2014). Ski-specific modes (i.e. skiing and roller skiing) constitute approximately 60% of the annual endurance training, where an increasing emphasis is put on the sport-specific endurance modes from the general preparation phase towards the competitive phase of the season (Tønnessen et al. 2014).

In contrast to XC skiers, NC athletes compete in a pursuit race. While the ~25 min race duration of NC athletes' 10-km race suggests similar capacities as for XC skiers to be important for performance (i.e. aerobic capacity, skiing efficiency, and finish sprint ability (Sandbakk and Holmberg 2014)), the complexity of a pursuit race over a varied terrain may cause different capacities to be advantageous for different aspects of the XC-race in NC. For example, performance on different terrain may relate to different physical capacities, and different pacing strategies may be necessary according to the athletes' placement in the XC skiing pursuit race after the SJ event, as well as to accommodate for athletes' limitations in anaerobic and aerobic energy supply and utilization. The optimal composition of the different physiological capacities deemed important for SJ and XC skiing performance to optimize performance in overall NC performance is of practical interest, but is difficult to examine scientifically. An analysis of the world's best athletes may thus serve as a model for the current benchmarks on the most important parameters.

Concurrent training of Nordic combined athletes

For successful NC performance, the athletes have to solve the extremely technically challenging task of a ski jump where vertical net force impulse at the take-off and low body mass are important characteristics, as well as skiing fast in the subsequent 10-km XC skiing race which requires a high aerobic capacity and upper-body power capacity. Physical strength and power training for SJ performance involves short-duration activities with maximal exercise intensity aimed towards increasing the capacity to perform maximal muscular contractions of a single repetition in a short time frame. Endurance training aimed to enhance XC performance, on the other hand, involves hundreds of submaximal muscular contractions to be performed at various exercise intensities over prolonged duration. This repetitive prolonged activity elicits adaptations in cardiovascular (Jones and Carter 2000), muscular (Abernethy et al. 1990; Hawley 2002), and metabolic (Baar 2014; Coffey and Hawley 2007) functions to increase the body's capacity to perform similar future exercise bouts. Performing long-term training of either training mode in isolation will ultimately produce a specific exercise-induced phenotype that is inherently different from one another (Abernethy et al. 1994; Abernethy et al. 1990; Coffey and Hawley 2007; Coffey and Hawley 2017; Coffey et al. 2006). Consequently, heavy resistance and aerobic endurance training is defined at opposite ends of the training adaptation continuum (Nader 2006), and the concurrent training of both is a complex challenge for coaches and athletes (see Table 2).

When Robert Hickson published the first scientific study on concurrent strength and endurance training in 1980, he demonstrated an impaired strength development when conducting concurrent training compared with strength alone (Hickson 1980). Hickson termed this impaired strength gain the *interference effect*. Since then, multiple studies on concurrent training have been conducted using various training protocols and durations (for review, see e.g. Leveritt et al. 1999), as well as animal studies investigating cellular pathways (Atherton et al. 2005). While the general assumption remains that performing concurrent strength and endurance training may decrease the effects of strength training on muscle strength (Hickson 1980), mass (Kraemer et al. 1995), and power (Wilson et al. 2012), the increasing bulk of studies have deduced that the universality of the interference effect is questionable in humans (Ellefsen and Baar 2019). Its presence and extent is rather likely associated with the training status of the individuals, type of muscles being trained, and the endurance training modes and protocols used.

Wilson and colleagues attempted to draw a definite conclusion on the interference effect from human studies in a meta-analysis in 2012. Here, they found muscle power, and not strength or hypertrophy, to be the major variable affected by concurrent strength and endurance training. Previous studies have also shown that force at high velocities is more affected than force at low velocities (Dudley and Djamil 1985), and Wilson et al. speculated that the decrements in muscle power result from either impairments in production of force at high velocity or rate of force development. Both of which, however, are viewed as important characteristics in successful SJ and NC athletes (Pääsuke et al. 2001; Rønnestad 2013). Moreover, Wilson et al. also demonstrated the degree of interference to be associated with the volume of endurance training, with both strength, hypertrophy, and power showing a negative association with both frequency and average duration of endurance workout.

While there are numerous athletic disciplines where a combination of both strength/power and endurance is required for successful performance, none are as extreme as NC. The simultaneous development of SJ and XC skiing capacity in NC athletes presents the ultimate challenge for coaches and athletes, and its extreme combination is under-explored. To understand the specific demands NC athletes face in competition, the capacities world class NC athletes possess to meet these demands, and how they compile their short- and long-term training to acquire these capacities, may provide us with a first insight into how high volumes of both strength/power and endurance training can be applied for simultaneous development. This would be of great relevance also for other concurrent power sports, and may provide a point of departure for future studies on this topic.

Table 2. The strength-endurance training-adaptation continuum

	STRENGTH/ POWER	⟷	ENDURANCE
Muscle contraction:	Short duration Maximal contractile activity		Prolonged duration Submaximal contractile activity
Main ATP source:	Anaerobic Phosphocreatine		Aerobic Glycolysis & lipolysis
Molecular adaptations:	Intracellular signaling in contractile proteins		Intracellular signaling in mitochondria proteins
Structural adaptations:	Muscle fiber hypertrophy		Mitochondria density
Functional adaptations:	↑ 1 RM ↑ Force net impulse ↑ Peak power		↑ VO_{2max} ↑ Utilization of VO_{2max} (lactate threshold) ↑ Efficiency of movement

PURPOSE OF THE THESIS

The main purpose of the current thesis was to investigate the performance demands of NC, the capacities required by NC athletes for reaching a world class level, and how NC athletes concurrently optimize the strength/power and endurance training required to succeed. This was examined through four comparative studies focusing on the following four research questions;

1) Which sport-specific laboratory capacities correlate with, and are best suited to predict, SJ, XC skiing and the overall performance in NC? (*Study I*)

   Approach: Twelve international NC athletes performed sport-specific SJ and XC skiing tests in the laboratory one day prior to participating in a NC World Cup event. Laboratory capacities and anthropometrics were correlated against performance in the SJ, XC skiing, and overall NC event, and linear regression analysis was performed to elucidate the most significant factors for performance.

2) How do world class NC athletes differ from specialist SJ and XC skiers in laboratory capacities and the compilation of seasonal training? (*Study II*)

   Approach: Sport-specific capacities, anthropometrics, and training data in five world class NC athletes were compared with world class specialists in SJ and XC skiing.

3) How do world class NC athletes periodize their concurrent strength/power and endurance training in successful seasons? (*Study III*)

   Approach: The training data of six world class NC athletes were analyzed in their most successful season to elucidate how they periodize their concurrent strength/power and endurance training across seasonal training phases.

4) How did an Olympic champion in NC periodize his training in order to develop technical and physiological characteristics over the four-year cycle preceding winning two Olympic gold medals? (*Study IV*)

   Approach: The training and laboratory test data from the four preceding seasons of winning two Olympic gold medals were analyzed in an Olympic champion in NC.

METHODS

The methods described here provide a summary and the reader is referred to the original papers for more detailed descriptions of the methods.

Subjects

In total, 17 Nordic combined (NC) athletes, 5 cross-country (XC) skiers, and 5 ski jumpers (SJ) participated in the four studies (Table 3). All athletes were considered world class. There was some overlap between the NC athletes participating in the studies, with one athlete participating in *Study II-IV*, four athletes participating in *Study II-III*, and one athlete participating in both *Study I* and *III*.

Table 3. Characteristics of the skiers in the four studies. For groups greater than 3 participants, values are reported as Mean ± SD.

	Athlete group	Number of subjects	Body height	Body mass	VO_{2peak}[a]	Vertical velocity[b]
Study I	NC	12	1.78 ± 0.06	65.8 ± 6.3	73.5 ± 4.3	2.41 ± 0.16
Study II	NC	5	1.82 ± 0.04	71.4 ± 3.5	70.1 ± 3.8	2.51 ± 0.15
	XC	5	1.85 ± 0.03	81.0 ± 2.9	78.2 ± 3.1	
	SJ	5	1.80 ± 0.02	65.7 ± 5.5		2.99 ± 0.17
Study III	NC	6	1.84 ± 0.03	72.5 ± 4.5	77.2 ± 2.8[a]	2.98 ± 0.11[b]
Study IV	NC	1	1.85	75.3	72.1	2.45

NC; Nordic combined, XC; cross-country, SJ; ski jumping, VO_{2peak}; peak oxygen consumption

[a] VO_{2peak} assessed in running in Study III and roller skiing in Study I-II and IV

[b] Vertical velocity assessed in squat jump in Study III and sport specific imitation jump in Study I-II and IV

The participants in *Study II-IV* had all reached the podium in World Cup events and the majority had also won Olympic and/or World Championship medals. *Study I* included a pool of international World Cup athletes of various performance records.

To compare NC athletes to specialist ski jumpers across all types of vertical jumps, supplementary data in countermovement and squat jumps for the participants in *Study II* are also included in this thesis.

Competition analyses

All World Cup events performed as an Individual Gundersen 10-km race (i.e. from 2008-09 to the 2017-18 season) were analyzed as supplementary data to this thesis from publicly available race reports at the International Ski Federation (FIS) Nordic combined web page (FIS 2018c). For all events, top-10 performers (G1-10) were compared against those finishing among 21-30 (G21-30), in order to analyze the relative contribution from SJ performance (i.e. time behind best jumper) and XC performance (i.e. XC course race time) to the group difference in total race time. The reason for choosing G1-10 and G21-30 was primarily that these groups are clearly different as performance groups while the lower ranked group is still motivated to give full effort in the XC race, since a top-30 result leads to valuable World Cup points. Rank 1-3 in the SJ, XC, and overall NC event, respectively, was also analyzed for their performance in each of the other two events.

Official competition results were also collected for a specific World Cup event in *Study I*, and correlated against laboratory capacities and anthropometrics measured the day prior to competition. Valid course and elevation profiles of the XC course were standardized with a Polar V800 GPS that collected position data at a 1 Hz sampling rate with integrated barometry that collected accurate elevation data. The course was then based on the course profile divided into uphill, flat, and downhill sections that made up 40%, 5%, and 55% of the 2 km lap, respectively (see Figure 9). During the XC race, each participant in *Study I* wore a Polar V800 that continuously measured their position at a 1 Hz sampling rate.

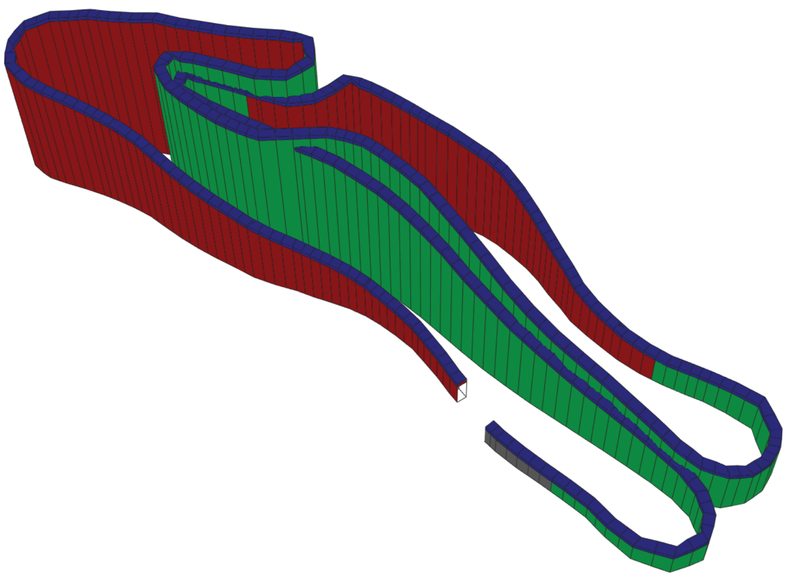


Figure 9. 2-km course profile that was completed 5 times in the 10-km World Cup event in *Study I*. Uphill, flat, and downhill sections of the course is represented by red, grey, and green colours, respectively.

Instruments and materials

Sport specific imitation jumps (IMIT) in *Study I-II* and *IV* were measured using Kistler force platforms (Kistler 9286AA, Kistler Instrument Corp, Winterthur, Switzerland) and analyzed in Matlab, whereas countermovement (CMJ) and squat (SQJ) jumps in *Study III-IV* and supplementary data to *Study II* were measured using SPSport force plate and Muskel-Leistungs-Diagnose 5.2 software (SPSport diagnosegeräte, GmbH, Austria).

Running tests in *Study III* were performed on a Woodway treadmill routinely calibrated for speed and incline. All roller-ski tests in *Study I-II* and *IV* were performed on a large motor-driven treadmill (see Figure 10), with non-slip rubber surface that allowed the skiers to use their own poles with special carbide tips. To minimize roller resistance variation, all participants within each study used the same pair of roller skis with standard wheels. Before each test, the roller skis were pre-warmed by 20 minutes of roller skiing on the treadmill and tested for rolling friction force with a towing test.

Respiratory variables were measured during all treadmill tests using open-circuit indirect calorimetry (Oxycon Pro, Jaeger GmbH, Hoechbeg, Germany). The instruments were calibrated against ambient air and commercial gas with known concentrations of O_2 (16.00%) and CO_2 (5.85%) before the start of each test day, and the flow transducer was calibrated using a 3-L high-precision calibration syringe (Calibration syringe D, SensorMedics, Yorba Linda, CA, USA). Heart rate (HR) was measured continuously with a HR monitor, and blood lactate concentrations ($[La^-]_b$) was taken from each skier's finger and measured with a blood lactate analyzer.

Figure 10.
A participant roller-skiing on a large motor-driven treadmill

Test protocols and measurements

Vertical jump tests

All jumps were performed using indoor training shoes, except for *Study I* where the participants used their own SJ boots. All jumps were performed with maximal effort, and 2-5 minutes break between each jump. Where the aim of the SQJ and CMJ is simply to maximize vertical velocity, the aim of the IMIT is to simultaneously gain sufficient angular momentum to end up in a flight-phase position caught by their coach (see Figure 11).

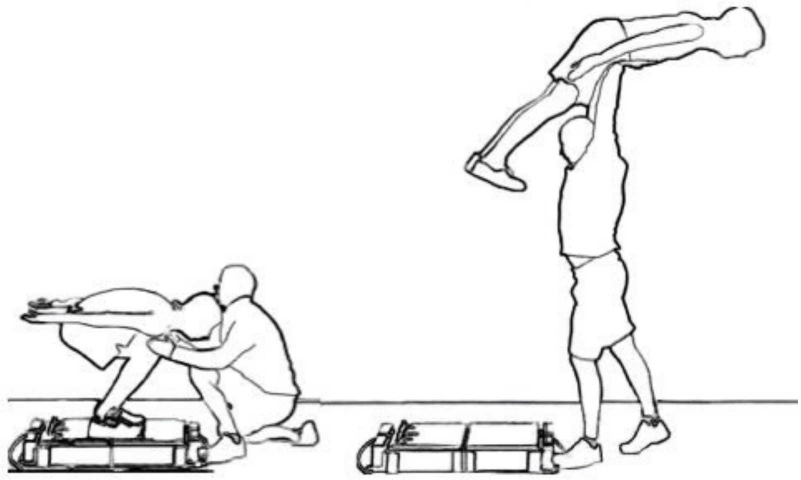


Figure 11. Illustration of an athlete performing a ski jump specific imitation jump on a three-dimensional force plate (Reproduced from *Study II*)

During the CMJ and SQJ, the hands were to be placed on the iliac crest throughout the jumps. Both SQJ and IMIT were initiated from the participants' individually chosen ski jump position after maintaining this position in a static fashion for at least 1 second.

The concentric push-off phase of all jumps was defined as the time period of upward movement before leaving the force plate. During this phase, the vertical velocity of the centre of mass was determined by the integration of acceleration over time, which, in turn, was calculated from the vertical ground-reaction forces. Vertical velocity (v_v) was calculated at the instant of maximum achieved vertical velocity.

Endurance tests

To measure physiological responses and kinematics, submaximal 5-min stages at a constant speed were performed in *Study I-II* and *IV*. $[La^-]_b$ was measured immediately after each stage. Gas exchange (i.e., VO_2 and VCO_2), HR, cycle length, and cycle rate were determined by the average of the last minute during each stage. Metabolic rate and gross efficiency were calculated from the abovementioned values (see calculations below) to compare efficiency of movement at the same submaximal speeds.

Peak aerobic capacity (VO_{2peak}) was assessed in incremental tests with increasing speed every minute (see Figure 12). The tests were considered to be a maximal effort if two of the following three criteria were met: (1) a VO_2 plateau with increasing exercise intensity, (2) respiratory exchange ratio (RER) above 1.10, and (3) $[La^-]_b$ exceeding 8 m*M*. VO_2 was measured continuously, and the average of the three highest 10-s consecutive measurements defined as VO_{2peak}. The highest HR values during the tests were defined as peak HR (HR_{peak}).

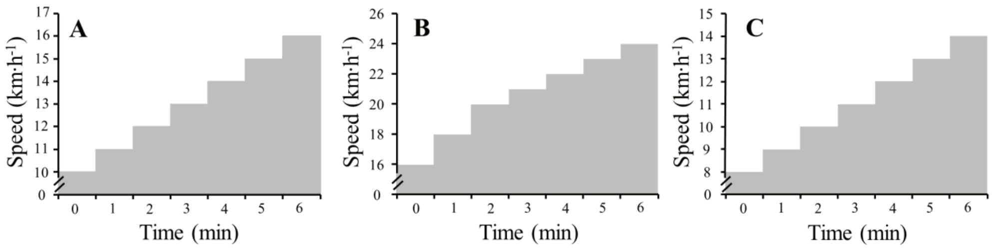


Figure 12. The different test protocols used to measure peak oxygen uptake in running at 10.5% incline (**A**), roller skiing at 5% incline using G3 skating technique (**B**), and roller skiing at 12% incline using G2 skating technique (**C**).

Gross efficiency and power calculations

Gross efficiency (GE) was calculated as the work rate divided by the total metabolic rate under steady-state conditions during 5-min submaximal stages on the treadmill. The work rate was calculated as the sum of power against gravity (P_g) and friction (P_f). The aerobic metabolic rate was determined from VO_2 and VCO_2 using the RER value and standard conversion tables (Peronnet and Massicotte 1991).

$$Gross\ efficiency = \frac{Work\ rate}{Metabolic\ rate} \cdot 100\%$$

$$\begin{aligned} Work\ rate &= P_g + P_f \\ &= [m \cdot g \cdot v \cdot \sin(\alpha)] + [m \cdot g \cdot v \cdot \mu \cdot \cos(\alpha)] \\ &= m \cdot g \cdot v \cdot (\sin(\alpha) + \mu \cdot \cos(\alpha)) \end{aligned}$$

With *m* being the body mass of the skier including equipment, *g* the gravitational constant, *v* the treadmill speed, *α* the treadmill incline, and *μ* the frictional coefficient.

Training diary analyses

The participants logged their day-to-day training in a specifically designed online training diary (olt-dagbok.nif.no) created by the Norwegian Olympic Sports Center (see Figure 13 for illustration). In these diaries, they recorded details about every training session and competition, including time spent on different forms of training, the intensity of all endurance training, and the number of repetitions for different forms of SJ. Endurance training intensity was monitored by HR and periodically supported by $[La^-]_b$ measurements in training, and categorized into three intensity zones, according to a modification of the Norwegian Olympic system's intensity scale (see Table 4). Non-endurance training such as SJ, strength/power sessions, stretching, and motor control, was registered from the start to the finish of the specific part of the session, including recovery periods between sets. Training data were exported and systemized in Microsoft Excel (Microsoft, Redmond, WA, United States) for further analysis.

Due to variations in how accurately the athletes of different sport disciplines in *Study II* logged their training, and based on dialogue with the national team coaches, we decided to analyze the training of one representative skier from each sport for the purpose of the study. These skiers were selected because they were regarded as representative of the average training values of the group both by their coach and the researchers and because the recordings of their training were deemed accurate.

Based on key periodization models in the literature and after personal communication with the athletes and coaches, the training year was divided into 5 phases; the transition phase (TP; May), general preparation phase (GP; June-October), specific preparation phase (SP; November-December), competition phase (CP; January-March), and regeneration phase (RP; April). In *Study IV*, the GP was further divided into GP1 (June-August) and GP2 (September-October) (see Table 5 for an overview of the training phases)

Table 4. The three intensity zones used in *Study II-IV*.

	Blood lactate concentration	**Heart rate zones (%HR_{max})**	**RPE (6-20)**
LIT Low Intensity Training	< 2 m*M*	60-81%	< 14
MIT Moderate Intensity Training	2-4 m*M*	82-87%	14-16
HIT High Intensity Training	> 4 m*M*	> 88%	17-20

RPE, Rating of perceived exertion; HR, heart rate

Table 5. The 6 phases of the training year with main training characteristics in key phases.

May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
TP	GP1			GP2		SP		CP			RP
	High endurance training volume			↑SJ focus		SJ/XC skate on snow		Travel and competitions			

TP, transition phase; GP, general preparation phase; SP, specific preparation phase; CP, competition phase; RP, regeneration phase; SJ, ski jumping; XC, cross-country.

Figure 13. Illustration of the electronic training diary

Statistical analyses

All data were tested for normal distribution using a Shapiro-Wilk test as well as by visual inspection. To compare the performance between G1-10 and G21-30 in the supplementary competition data and the different laboratory parameters between athlete groups in *Study II*, a parametric independent *t* test and nonparametric Wilcoxon procedure was performed. In *Study I*, correlation analysis between laboratory and field performance was conducted using the parametric Pearson's r or the nonparametric Spearman's ρ correlation coefficient. Multiple regression analyses using enter-method with blocks of 1-2 independent variables were employed to predict performance in SJ, XC, and overall NC performance. To identify whether there were statistically significant training differences between the 5 training phases in *Study III* and/or differences between the four type of jumps used in *Study I-IV*, a 1-way repeated-measure analysis of variance (ANOVA) was employed. Where the ANOVA revealed a significant effect, a post hoc test with Bonferroni correction for multiple comparisons was used to determine the location of variance. Variables that were found to be significantly non-normally distributed were analyzed using a related-samples Friedman rank test. In all studies, the statistical analyses were performed using SPSS software (SPSS Inc, Chicago, IL), with an alpha value of 0.05 used as the level of statistical significance.

SUMMARY OF RESULTS

Performance demands

167 individual World Cup events employing the Individual Gundersen method over 10-km were analyzed between the 2008-09 and 2017-18 seasons. On average for all events, G21-30 were 6.0% behind G1-10 in total race time. The average difference in SJ and XC performance explained respectively 57% and 43% of the total race time difference (i.e. 53 s and 40 s out of an overall 93 s group difference). The two groups were significantly different in all performance measures across all seasons (all $p < 0.01$), except from XC performance in the 2015-16 season ($p = 0.205$) (Figure 14).

Of the 501 top 3 rankings in overall NC performance, 36% of the cases were also top 3 in SJ performance and 26% top 3 in XC performance. Of the top 3 in either SJ or XC performance, only 5% were top 3 in the other event (Figure 15).

In the specific world cup event in *Study I*, 60.8 ± 0.9, 4.1 ± 0.2, and 33.8 ± 0.8 % of the 10-km XC race was spent in respectively uphill, flat, and downhill terrain. Mean skiing speed of the total race was 6.7 ± 0.3 $m \cdot s^{-1}$, where the fastest skiers had a higher mean skiing speed in all segments compared with the best ski jumpers (Figure 16).

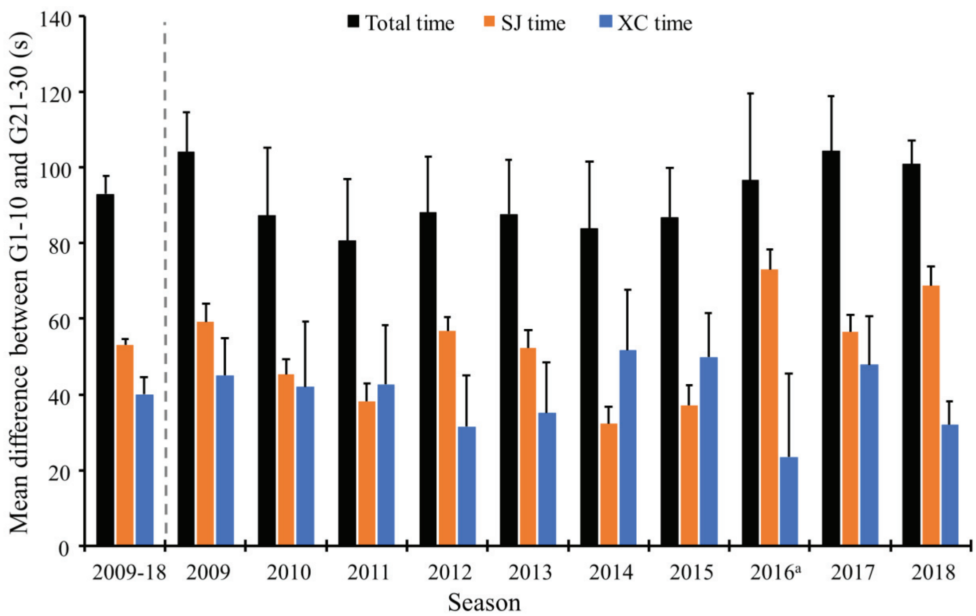


Figure 14. Mean difference (± standard error) between top-10 performers (G1-10) and those finishing among ranks 21 to 30 (G21-30) across seasons between 2008-09 to 2017-18 in total race time, as well as the time lost in ski jumping (SJ) and cross-country (XC) race time.

[a] In the 2015-16 season, the points awarded per meter jumped in large hill events were raised from 1.5 to 1.8

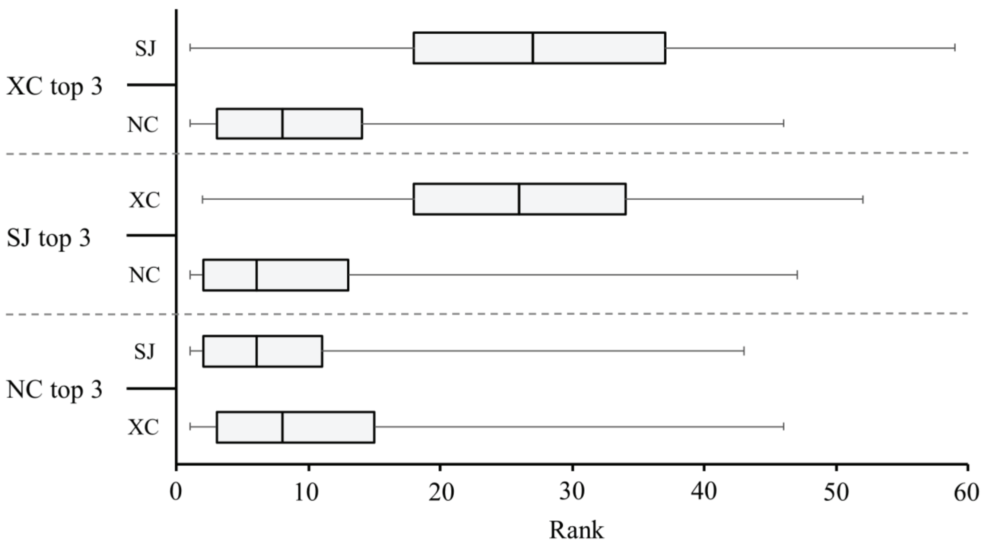


Figure 15. Median rank (with min, max, and interquartile range including 50% of the ranks) in ski jumping (SJ), cross-country (XC), and overall Nordic combined (NC) performance in all 10-km NC World Cups between 2008-09 and 2017-18 seasons in the top 3 performers of each category.

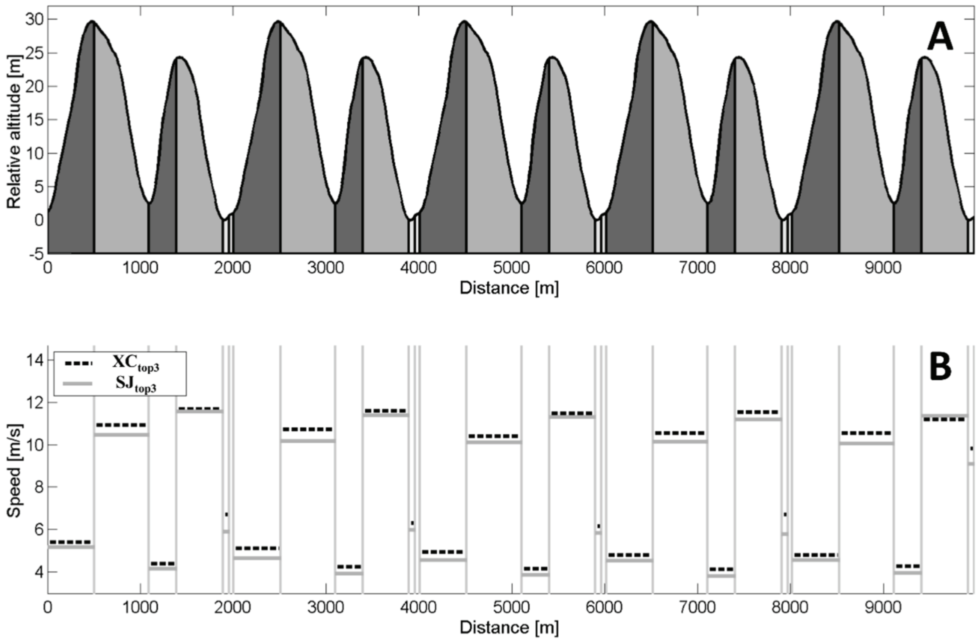


Figure 16. 10-km race course profile from *Study I*, with average speeds in each segment. The upper graph (**A**) represents the race course profile of the 10-km cross-country race with the relative elevation with regard to zero (start) and uphill, flat, and downhill sections in different tones of gray. The lower graph (**B**) represents the average speed ($m \cdot s^{-1}$) in the defined sections for both the top 3 ranked cross-country skiers (XC_{top3} in black stapled lines) and the top 3 ranked ski jumpers (SJ_{top3} in gray solid lines). (Reproduced from *Study I*)

Laboratory capacities

Validation of laboratory capacities (Study I)

Regression analyses with various laboratory capacities and anthropometric characteristics in 12 NC World Cup athletes as independent variables, resulted in the following three equations as the best predictions for SJ (1a,b), XC (2), and overall NC (3) performance respectively;

(1a) $SJ\ performance\ (pts) = 8.51 + 35.90 \cdot v_{vIMIT} - 0.58 \cdot body\ mass$

V_{vIMIT} in $m \cdot s^{-1}$, body mass in kg, $F_{(2,9)} = 10.41$, $p < 0.01$. The factors included all significantly contributed to model 1a (all $p < 0.05$) which explained 70% of the variance in SJ performance.

When expressing SJ performance as time rather than the sum of distance and compensation points, as presented in *Study I*, it did not affect the statistical outcome;

(1b) $SJ\ performance\ (min) = 5.26 - 2.92 \cdot v_{vIMIT} + 0.05 \cdot body\ mass$

V_{vIMIT} in $m \cdot s^{-1}$, body mass in kg, $F_{(2,9)} = 10.08$, $p < 0.01$. The factors included all significantly contributed to model 1b (all $p < 0.05$) which explained 71% of the variance in SJ performance.

(2) $XC\ performance\ (min) = 40.29 - 0.12 \cdot VO_{2peak} - 0.64 \cdot double\ poling\ power$

VO_{2peak} in $ml \cdot kg^{-1} \cdot min^{-1}$, double-poling power in W·upper-body-lean-mass^{-1}, $F_{(2,8)} = 8.63$, $p = 0.01$. VO_{2peak} significantly contributed to model 2 ($p < 0.05$), while double-poling power showed a tendency ($p = 0.07$). Model 2 explained 68% of the variance in XC performance.

(3) $NC\ performance\ (rank) = 156.45 - 1.75 \cdot VO_{2peak}$

VO_{2peak} in $ml \cdot kg^{-1} \cdot min^{-1}$, $F_{(1,10)} = 7.47$, $p = 0.02$. Model 3 explained 43% of the variance in overall performance.

Comparison to ski jumping and cross-country skiing specialists (Study II)

Compared with SJ, NC athletes showed 7% and 16% lower v_v in respectively SQJ and IMIT ($p < 0.05$, Figure 17), and demonstrated 9% higher body mass and 4% higher BMI ($p < 0.05$, Figure 18A). SJ and NC athletes reduced their v_v by respectively 10% and 18% from SQJ to IMIT ($p < 0.05$).

NC athletes had 12% lower body mass and 11% lower BMI than XC skiers ($p < 0.05$, Figure 18A), showed 10% lower peak treadmill speed, and 22% lower absolute and 12% lower body-mass normalized VO_{2peak} (all $p < 0.05$).

At the same absolute submaximal speed, NC athletes had a higher HR, 1.8 m*M* higher $[La^-]_b$, and a higher RER (all $p < 0.05$) than XC skiers, whereas neither body-mass-normalized VO_2 nor GE differed between groups.

No significant differences between groups in cycle length or cycle rate were found at 14 $km{\cdot}h^{-1}$. During the maximal test, NC athletes employed 7% shorter cycle lengths and correspondingly 7% higher cycle rates at 20 $km{\cdot}h^{-1}$, whereas at peak speed, cycle lengths were 11% shorter than those of XC skiers (all $p < 0.05$), with cycle rates being close to identical between groups (Figure 19).

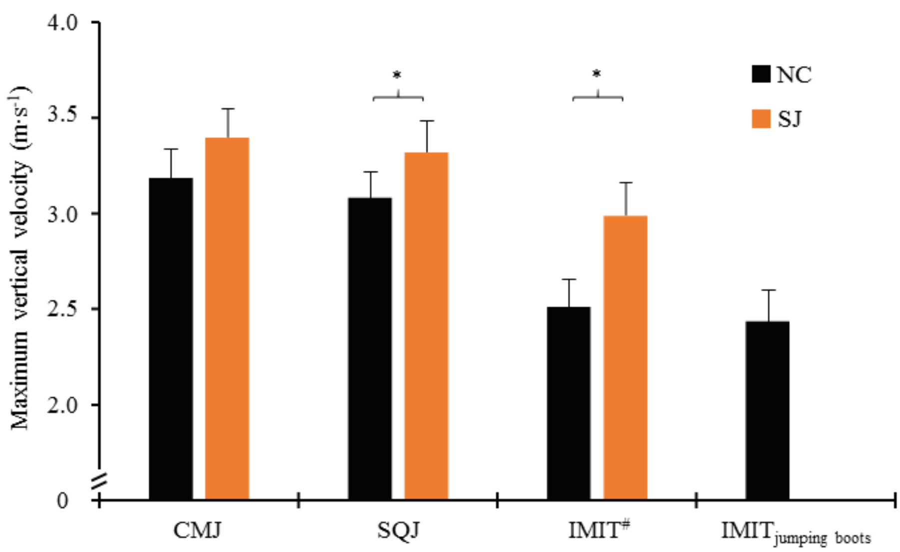


Figure 17. Maximum vertical velocity achieved in countermovement (CMJ), squat (SQJ), and sport-specific imitation (IMIT) jumps in world class ski jumpers (SJ) and Nordic combined (NC) athletes.
* Significant difference between SJ and NC ($p < 0.05$)
# Significantly different from CMJ and SQJ ($p < 0.05$) in both SJ and NC

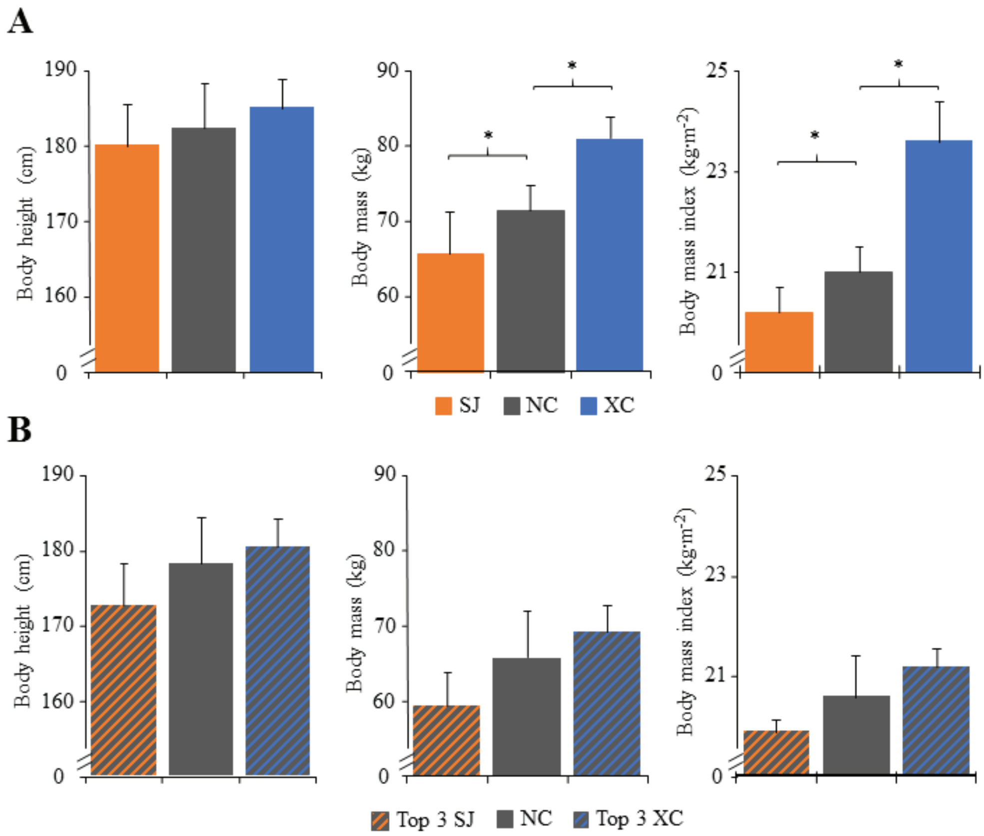


Figure 18. Anthropometrics of world class Nordic combined (NC) athletes, ski jumpers (SJ), and cross-country (XC) skiers. N = 5 for each group from *Study II* at the top (**A**), n = 12 NC athletes from *Study I* at the bottom (**B**) compared to the top 3 SJ and XC within the group of NC athletes.
* Significant difference between groups ($p < 0.05$)

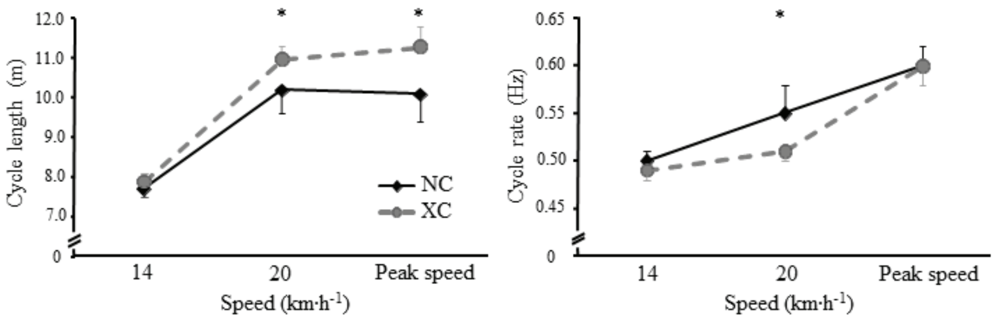


Figure 19. Cycle characteristics determined at submaximal and individual peak speed in world-class Nordic combined (NC) athletes and cross-country (XC) skiers when roller ski skating at 5% incline using G3 skating technique.
*Significant difference between the two groups, $p < 0.05$.

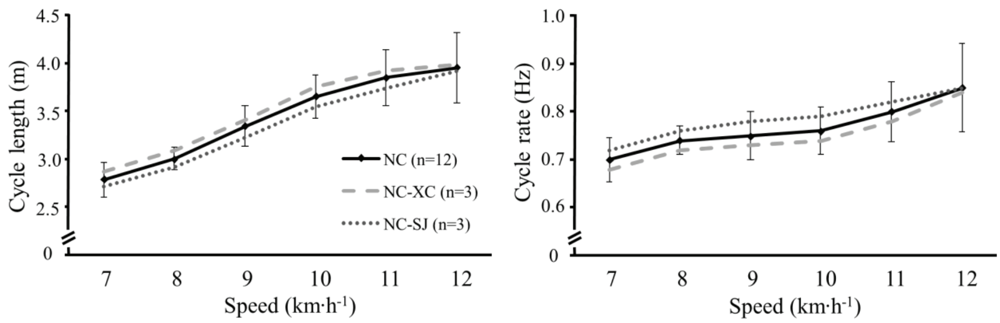


Figure 20. Cycle characteristics determined at incremental speed protocol on roller ski skating at 12% incline using G2 skating technique in twelve World Cup Nordic combined (NC) athletes as well as the three best cross-country (XC) skiers and ski jumpers (SJ) within the group.

Long-term physical development (Study IV)

The Olympic champion in *Study IV* varied less than 5% in SQJ and CMJ v_v during the four-year cycle, whereas the v_v in IMIT showed a 14% increase from 2.14 to 2.45 $m \cdot s^{-1}$ in the same period (Figure 21A).

The participant increased his aerobic capacity by 0.78 $L \cdot min^{-1}$ from 2010-11 to 2012-13 season (Figure 21B), whereas his body mass normalized VO_{2peak} was ~70 $ml^{-1} \cdot kg^{-1} \cdot min^{-1}$ across all seasons investigated.

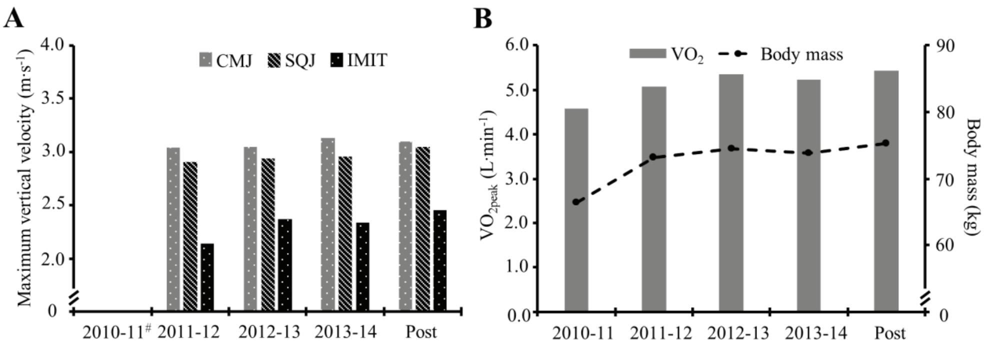


Figure 21. Laboratory capacities determined during the general preparation phase from 2010-11 to 2013-14 season, as well as immediately after the Olympic Games (Post) in an Olympic Nordic combined Champion. Vertical jump tests displayed to the left (**A**), and peak oxygen uptake from incremental roller-ski tests and body mass displayed to the right (**B**).

[#] The participant did not perform any vertical jump tests in the season of 2010-11.

CMJ, countermovement jump; SQJ, squat jump; IMIT, sport-specific imitation jump; VO_{2peak}, peak oxygen consumption

Training composition

Annual training composition of a world class NC athlete was descriptively compared against a world class SJ and a XC specialist in *Study II*, the annual training periodization investigated in a group of world class NC athletes in *Study III*, and a four-year training periodization cycle investigated in an Olympic NC champion in *Study IV*.

Table 6. Summary of Nordic combined training data from the total of 10 seasons investigated in studies II-IV after adjusting for overlap between studies.

		Mean	Range
Training volume	(hrs·season^{-1})	863	723-1008
Endurance	(hrs·season^{-1})	545	462-635
XC skating	(hrs·season^{-1})	252	193-294
XC skating[a]	(%)	46	36-52
LIT/MIT/HIT[a]	(%)	89/6/5	
Non-endurance	(hrs·season^{-1})	306	219-376
SJ training	(hrs·season^{-1})	183	105-276
Stretching	(hrs·season^{-1})	47	19-87
Other	(hrs·season^{-1})	15	3-61

XC; cross-country, LIT; low-intensity training, MIT; moderate-intensity training, HIT; high-intensity training, SJ; ski jumping
[a] Percent is given as percentage of total endurance training volume

Annual training differences to ski jumping and cross-country specialists (Study I)

NC, SJ, and XC skiers all trained approximately 800-900 annual training hours, where the NC athlete differed to the specialists in the amount of non-endurance and endurance training, respectively (Figure 22). The NC athlete performed approximately half the number of SJ specific sessions and outdoor ski jumps compared to the SJ specialist (Figure 22A), but with lower average session duration and time per ski jump. Compared to the XC specialist, the NC athlete performed two-thirds of the annual endurance training hours where the difference in training volume was mainly found in low- (LIT) and moderate-intensity training (MIT) in the classical technique (Figure 22B). The NC athlete performed similar training distribution model of his non-endurance and endurance training as the respective specialists (Figure 23).

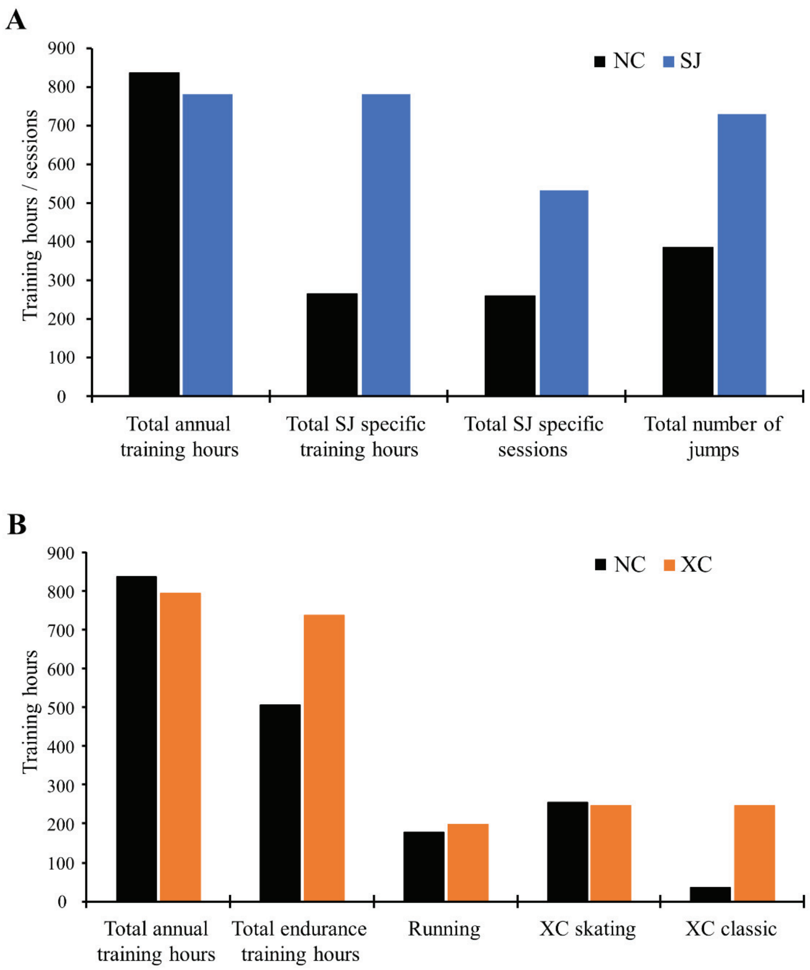


Figure 22. Annual training hours, sessions, and jumps in a World Class ski jumper (■ SJ) and Nordic combined athlete (■ NC) (**A**), and annual training hours in a World Class cross-country skier (■ XC) and NC (**B**)

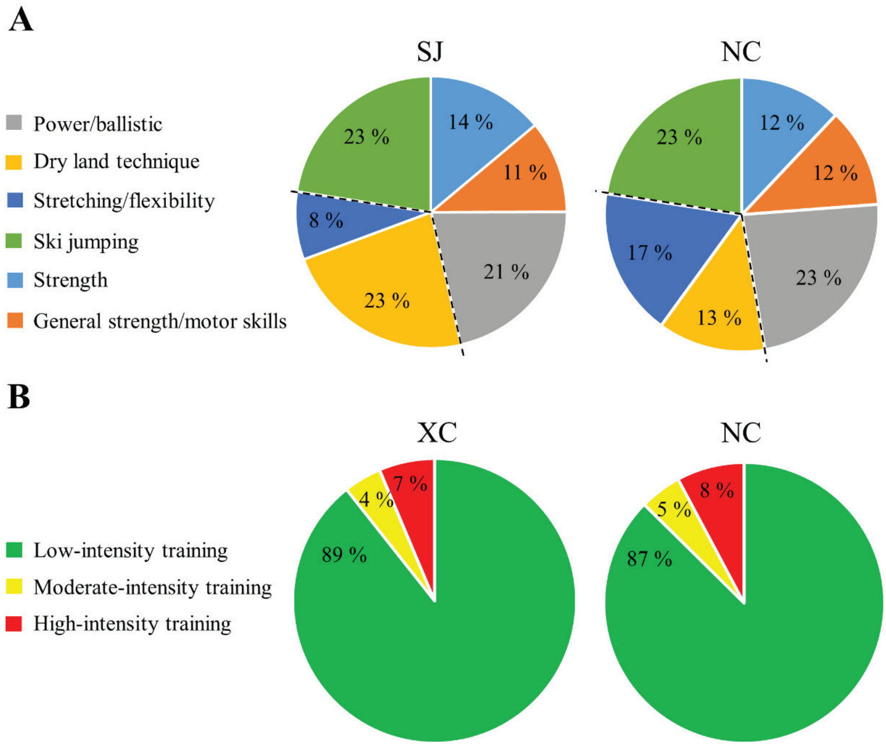


Figure 23. Distribution of non-endurance training hours in a world class ski jumper (SJ) and Nordic combined (NC) athlete (**A**) and intensity distribution of annual endurance training in a world class cross-country (XC) skier and a NC athlete (**B**).

Annual training periodization (Study III)

When comparing seasonal training data of a group of World Class NC athletes, the recovery phase of the season (RP) was found to be a major unloading phase and significantly different from all other phases in terms of total training volume ($p < 0.01$), training frequency ($p < 0.01$), and the time used for ski jump and strength/power training ($p < 0.05$).

Total training volume showed a progressive decrease from GP to CP – significantly higher in GP than SP and CP ($p < 0.05$), and significantly higher in SP than CP ($p < 0.01$) (Figure 24) – but no differences between any of the phases in terms of training frequency. The proportion of non-endurance training to total training volume was significantly lower in GP than in CP ($p < 0.05$).

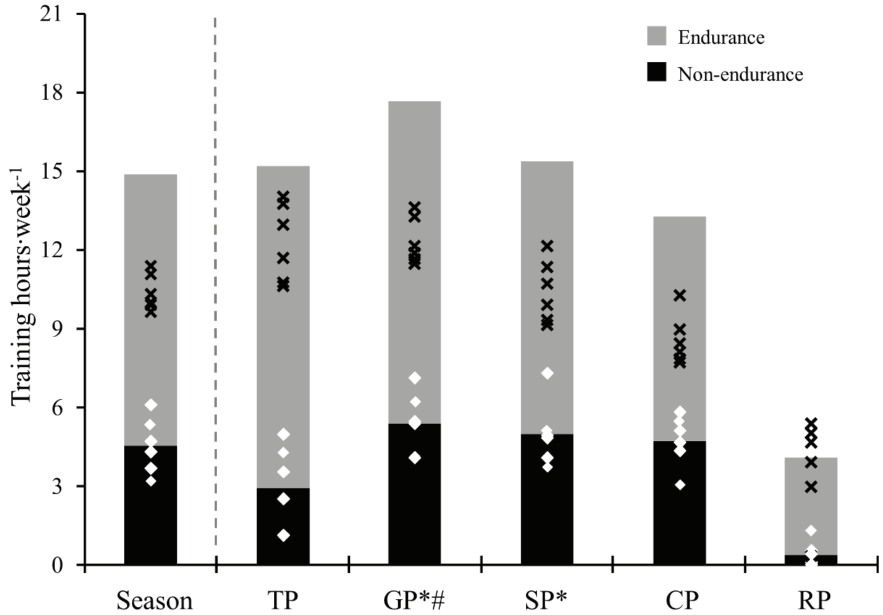


Figure 24. Average weekly endurance and non-endurance (i.e. all strength, power, and ski jump training) training hours for the 6 world-class Nordic combined athletes during the season as a whole, transition phase (TP), general preparation phase (GP), specific preparation phase (SP), competition phase (CP), and regeneration phase (RP). Bars represent group mean distribution. Black crosses represent individual values for endurance training; white rotated squares represent individual values for non-endurance training.
* Significantly different than CP; # Significantly different from SP

Training volume in LIT was significantly higher in TP and GP than in the other phases, and training volume in MIT significantly higher in GP than in CP ($p < 0.05$). There were no significant differences among any of the 5 phases regarding training volume or frequency in HIT. The volume of cross-training (i.e. endurance training not employing XC skating technique) was significantly higher in TP and GP than all other phases ($p < 0.05$).

Table 7 describes typical examples of the daily training during one week at three different training camps with different weighing of SJ and XC training in the GP, as well as one training week in CP. This illustrates the type of periodization used by NC athletes, as well as their sequencing of sessions during these different periods.

Long-term training periodization (Study IV)

The athlete in *Study IV* recorded 804, 824, 1008, and 950 training hrs·season^{-1} in the Olympic cycle preceding winning two Olympic gold medals, distributed across 472, 519, 582, and 585 sessions. Whereas the amount of general strength/power training varied as a sine wave between 90 and 140 hrs·season^{-1}, the amount of SJ specific training and number of IMITs increased steadily each season (Figure 25).

The athlete reported that the compilation of strength/power sessions early in the cycle was focused toward building lower-body muscle-mass and maximal strength (i.e. high-resistance-low-velocity), whereas more high-velocity exercises in SJ specific movement patterns were progressively emphasized towards the Olympics. The participant also focused specifically on improving ankle-flexibility and hip/core control in the SJ specific movement early in the cycle, and at the same time technically aimed to (1) reduce fluctuations of the centre of mass in relation to the centre of pressure in the in-run and (2) have the centre of mass placed vertically above the centre of pressure (i.e., lower lever-arm) during the take-off phase in the SJ hill.

The athlete performed a polarized endurance periodization in all seasons, with the overall variation in endurance training volume mainly manipulated by LIT. The amount of MIT and HIT was almost identical in all four seasons, except from a 22% decrease in the amount of MIT from year 3 to the Olympic season.

The participant included sprints in nearly all LIT sessions on roller skis and skis, while sprints at the end of some of the MIT/HIT sessions stressed the ability to maintain a well-executed technique when fatigued.

The amount of endurance training was similar between specific and unspecific training modes (i.e., 45, 44, 47, and 54% XC skating in the respective seasons from 2010-11 to 2013-14). More than two-thirds of MIT and HIT was performed on skis or roller-skis in all seasons, whereas for LIT 40-50% XC skate was performed.

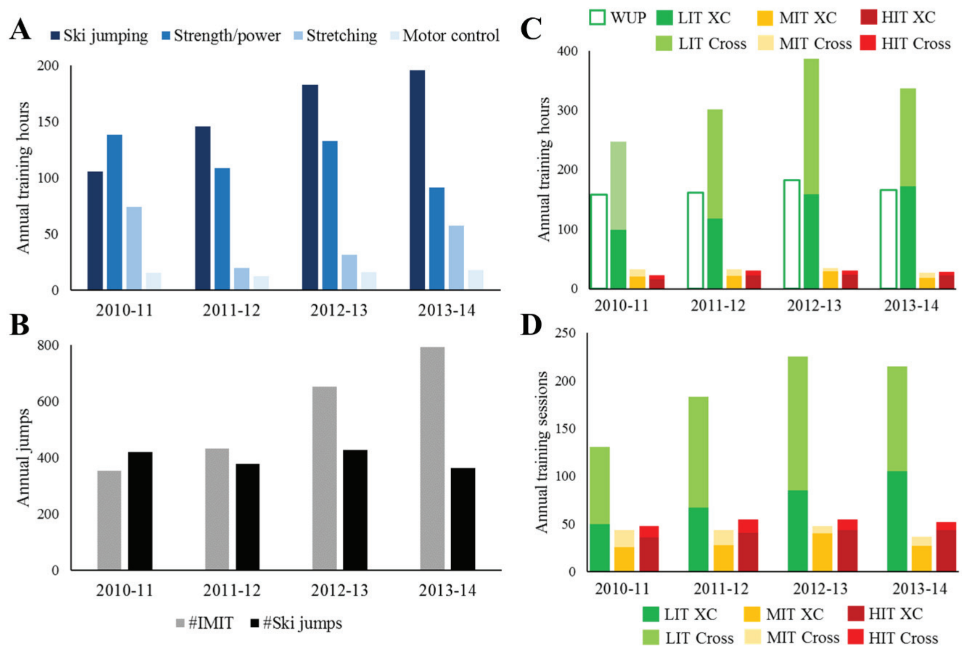


Figure 25. Annual non-endurance training hours (**A**) and number of jumps (**B**), as well as annual endurance training hours (**C**) and sessions (**D**) from the seasons 2010-11 to 2013-14 in an Olympic champion in Nordic combined. (Reproduced from *Study IV*)

IMIT, dry-land imitation jump of a ski jump; WUP, time spent for warm-up, cool-down, and recovery; LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training; XC, cross-country session employing skating technique; cross, endurance session not employing cross-country skating technique.

Table 7. Examples of the training performed during training camps with different weighing of ski jumping (SJ) and cross-country (XC) skiing in the general preparatory phase (June-October), as well as a training week in the competition phase (January-March)

Day	XC skiing focus	SJ focus	Mixed focus	Competition week
Mon	2 h SJ (HS105) 1.5 h LIT XC	2.5 h SJ (HS105) Power session	Power session 1 h LIT running	Recovery/2 h LIT XC (depending on prior load)
Tue	6x8 min MIT XC 1.5 h LIT running	2 h SJ (HS105) 1.5h SJ (HS140) + 1 h LIT running	2 h SJ (HS105) 1.5 h LIT XC	Power session 1.5 h LIT XC
Wed	2.5 h LIT XC 1.5 h LIT XC + 12x8s sprints	Technique session 6x5 min HIT running	4x5 min HIT XC Strength session	2 h SJ (HS105) 5x8 min MIT XC
Thu	6x5 min HIT XC Technique session	2.5 h SJ (HS105) 1.5 h SJ (HS140) + 1 h LIT running	2.5 h SJ (HS140) 5x8 min MIT running	Travel 1 h LIT running + short power
Fri	4x6 min HIT XC 1 h LIT running + power	Power session 1 h LIT XC (double poling)	Power/technique session 2 h LIT XC	4 h SJ (competition hill) 1 h LIT XC
Sat	2 h LIT XC Strength session	1 h SJ (HS140) Strength + 1 h technique session	2 h SJ (HS105) 1.5 h LIT running	SJ competition XC competition
Sun	6x8 min MIT XC 1.5 h LIT running	2.5 h SJ (HS140) 1.5 h LIT running	2x10 min MIT + 3x5 min HIT XC 2 h LIT running	SJ competition XC competition

Abbreviations: LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training
Note: XC skiing performed as roller-ski skating. SJ duration listed includes 45 min of warm-up, stretching, and preparation of equipment before the jumps in addition to 4-6 jumps·session^{-1}. MIT and HIT sessions always included ~40-60 min of LIT in addition to what is listed, performed as warm-up and cool-down. HS105 and HS140 indicate SJ hills where the profile is constructed for maximum jumping distances of 105 and 140 m, respectively. Strength session typically involves 15 min of LIT warm-up (running/cycling) followed by 45 min of core/stabilization exercises. Power sessions involves 10-20 min of LIT warm-up (running/cycling), 10 min of leg curl/extension 6-10 RM, followed by 30-60 of power exercises performed movement-specific for ski jumping, with maximal effort and low number of repetitions (<4) with or without additional weight and ballistic elements. Technique sessions consisted of SJ imitations on dry land where the athlete tries to replicate the same type of movement as on the take-off in the jumping hill.

DISCUSSION

This thesis provides novel information on the performance demands of NC, the capacities required by NC athletes for reaching a world class level, and how NC athletes concurrently optimize the extreme strength/power and endurance training required to succeed. The main findings were that

1. Vertical velocity (v_v) obtained in imitation jump (IMIT) and body mass provided the best prediction of ski jumping (SJ) performance whereas body mass normalized VO_{2peak} in roller-skiing and double-poling power provided the best prediction of cross-country (XC) performance;
2. World class NC athletes differed 10-17% in various laboratory capacities and performed half the SJ specific sessions and two-thirds of the endurance training hours as SJ and XC specialists, respectively;
3. World class NC athletes performed ~850 annual training hours with more than 60% of these being endurance training. Although training frequency remained relatively constant throughout the season, the total training volume was gradually reduced from the general preparation phase (GP) to competition phase (CP) with low-intensity (LIT) endurance training acting as the main manipulator. For both endurance and SJ specific training, the training patterns logically followed the principle of specificity, with more general training in the initial training periods, followed by more competition-specific loading in CP;
4. The Olympic NC Champion progressively increased his endurance training over the first three initial seasons of the four-year cycle, before reducing endurance training by 12% in the Olympic season. While maintaining his CMJ vertical jump velocity at ~3 $m \cdot s^{-1}$, despite an increase of 7 kg overall body-mass, the participant improved his vertical jump velocity of sport-specific IMITs with 0.31 $m \cdot s^{-1}$ and roller-ski VO_{2peak} with ~0.8 $L \cdot min^{-1}$ concomitant with an almost twofold increase of annual IMITs and an increase of ~200 annual endurance training hours in the four-season cycle. An emphasis on improving sprint ability in XC skiing was present in all seasons, a determining factor since both Olympic gold medals were won in the final sprint.

Performance demands

To succeed in NC, the athletes have to perform well in both SJ and XC skiing. Of all individual 10-km NC World Cup events since the 2008-09 season, 75% of the NC podium rankings were among top 15 in both the SJ and XC part of the competition. Comparing the two performance groups G1-10 and G21-30 demonstrates that the relative contribution from SJ and XC performance to overall NC performance level has been similar since the introduction of 10-km race (~55% versus ~45% contribution of SJ and XC performance, respectively). The contribution from XC performance was relatively higher only in the seasons of 2013-14 and 2014-15. In the 2015-16 season, FIS regulated the points awarded per meter jumped in the large hill from 1.5 to 1.8 $pts \cdot m^{-1}$, thus increasing the contribution of SJ to overall NC performance. The 2015-16 season was also characterized with generally high temperatures and little snow across Europe, resulting in shorter XC courses (i.e. less uphill segments) with artificial snow that was salted and unusually icy. Consequently, this may have influenced the XC race times and time differences between athletes, creating an unrepresentative low contribution of XC course time to overall NC performance. This may also explain the non-significant difference in XC performance between the two performance groups in this season.

Of the three best ski jumpers in each NC World Cup event, only 5% were also among the three fastest XC skiers in the event. This might be due to differences in phenotypes, but it is also different tactics applied according to the placement after the SJ competition. In the single competition in *Study I*, the three fastest XC skiers in the subject pool skied faster than the three best jumpers in all segments of the XC race. However, they also started the XC race as number 39-44, while the best jumpers in the subject pool started as number 5-18 and might have used different pacing strategies to achieve the same overall performance. Due to the different tactics of a pursuit race, determining the competitive demands is challenging. Rather, the various capacities of elite NC athletes may serve as a model for the current benchmarks on the most important parameters.

Laboratory determinants for performance

Ski jumping

While all phases of a ski jump are important and dependent on the success of the previous one, the take-off is widely considered as the most important for overall success (Schwameder 2008). Here, the athlete aims to maximize vertical velocity (v_v) from an aerodynamically convenient squat position within ~0.3 s, simultaneous as producing enough angular momentum to reach optimal flight position as early as possible. Consequently, that SJ performance correlated significantly with both v_v and time of push-off in IMIT in *Study I*, while v_v together with body mass were best suited to predict SJ performance, was as hypothesized. These findings are in accordance with established performance characteristics of successful ski jumpers (Müller and Schwameder 2003; Müller 2009), as well as with the group difference found between world class NC athletes and SJ specialists in *Study II.*

When all else is equal, a low body mass enables the athlete to optimize the v_v at take-off (i.e. net force impulse leads to change in $m \cdot v_v$, and a difference in v_v proportional to the body mass difference is expected) in addition to lowering the gravitational force during the flight phase, thus increasing the jump distance. The fact that body mass and BMI were higher in NC athletes than SJ specialists in *Study II* was not surprising because, in contrast to SJ, NC athletes need to develop upper-body muscle-mass to effectively pole while XC skiing. However, the 9% higher body mass found in NC did not fully coincide with the 17% difference in v_v between the two groups during IMIT in *Study II*, indicating that NC athletes are not only heavier than SJ but also have a lower force impulse capacity.

Body mass alone did not show a strong correlation coefficient ($r_s = -0.511$, $p = 0.089$) with SJ performance among NC athletes in *Study I*, as one might have expected. However, a lower body mass will not only reduce the gravitational force in the flight phase, it will also reduce the horizontal momentum at take-off which in turn will have a negative effect on jump distance. In-run speed has been found to both significantly correlate with jumping distance in jumping events (Virmavirta et al. 2009) as well as differentiating NC athletes and SJ specialists jumping the same distance (Janura et al. 2011). Still, a low body mass has been found to have an overall positive effect on SJ performance in simulation studies (Schmölzer and Müller 2002), in addition to being beneficial for maximizing v_v at take-off. Therefore, if we assume that lowering body mass when all else is equal is beneficial for SJ performance on an individual level, it is likely that the inter-individual differences in the production of v_v in IMIT is the most determining factor among elite NC athletes with body mass being a contributing factor to performance.

The technical complex movement of a ski jump is a skill that takes years and thousands of repetitions to optimize, and very few jumpers are able to maintain a top performance level over several seasons as the margins in the execution are so small and can so easily be lost. That v_v in IMIT and not SQJ was found to significantly correlate with SJ performance in *Study I* was therefore not surprising. While a well-developed vertical jump capacity may be argued to be a prerequisite for elite level in SJ, it is primarily how much v_v an athlete is able to produce in the sport specific movement that is decisive. This is also supported by world class NC athletes producing only 7% lower v_v in SQJ compared to SJ specialists, while the difference is increased to 16% in IMIT (*Supplementary data to Study II*). The Olympic champion investigated in *Study IV* was therefore highly dedicated to mental training to help transfer his vertical jump capacity to the sport specific movement of an IMIT and thereafter to the jumping hill. Although force plates have been used to study simulation jumps for more than 50 years (Müller and Schwameder 2003), there are still no guidelines of quantifiable variables to describe successful movement strategies in dry-land simulation jumps. While the v_v in IMIT may serve as an important end measurement, future studies should strive to elucidate methods to particularly describe the interplay with producing angular momentum.

Cross-country skiing

Competing at 10-km races with a race duration of ~25 min, where ~60% of the time is spent in uphill terrain (*Study I*), the demand for aerobic energy supply is high in NC athletes (Gastin 2001). Consequently, it was as hypothesized that body-mass normalized VO_{2peak} in roller-ski and double-poling power were best suited to predict XC performance in *Study I*. The importance of a high aerobic capacity is well established in several endurance sports (Jones and Carter 2000), including XC skiing, but *Study I* is the first study to validate the association to competitive performance among elite NC athletes. When comparing world class NC athletes to XC specialists in *Study II*, NC athletes achieved 10% lower VO_{2peak} that corresponded with 9% lower peak speed. This difference in VO_{2peak} is also similar to what has been found in a recent study when comparing Olympic NC and XC skiers in running VO_{2max} (Tønnessen et al. 2015a). Subsequently, the higher VO_{2peak} allowed the XC skiers in *Study II* to ski at the same absolute submaximal speed with lower physiological stress. The lower peak speed achieved by NC athletes was followed by shorter cycle lengths than the XC skiers, but not by cycle rate differences. These are all typical patterns when comparing performance-level differences in the skating technique employed by XC skiers (Sandbakk et al. 2011a; Sandbakk and Holmberg 2014; Sandbakk et al. 2010; Sandbakk et al. 2011b), and seem to apply also to differences between NC and XC athletes. Although the group size of intra-specialists in *Study I* is too small to make any conclusions, these performance patterns also appear to be valid when comparing elite NC athletes of different XC performance level.

The importance of upper-body power for XC performance has received a considerable focus in the last two decades, as it has been associated with enabling skiers to use longer cycle lengths at the same speeds and reach higher maximal speed in easy to moderate inclines (Grasaas et al.

2014; Millet et al. 1998; Sandbakk et al. 2013a). The finding that double poling power significantly correlated with XC performance in *Study I* was therefore no surprise. Although no apparent association was present between upper-body power and cycle length or peak speed during incremental exercise in *Study I*, the roller skiing in this study was performed using the G2 skating technique, where upper-body capacity is less dominant compared to G3 skating used in *Study II* (Millet et al. 1998). Still, comparing the intra-specialists among the elite NC athletes did show tendency of group differences in cycle length across the full range of speeds similar to that found between world class NC athletes and XC skiers in *Study II*. However, as the performance groups in *Study I* only consisted of three athletes each, and we did not include any upper-body power measurement in *Study II*, we may only speculate on the association between upper-body power and cycle length in these studies.

Skiers with a better developed technique and higher efficiency of movement will at the same metabolic rate produce higher work rates. That no significant correlation was found between GE and XC performance in *Study I* was therefore in contrast to what could be hypothesized from previous studies on XC skiers (Sandbakk et al. 2013b; Sandbakk and Holmberg 2014; Sandbakk et al. 2010). However, while Sandbakk and colleagues have found GE to differ between performance levels within gender in male (2010 & 2013) and female (2013) XC specialist skiers, no difference in GE was found when comparing performance-matched men and women (2013). The latter is in accordance with the finding in *Study II*, where world class NC athletes did not differ in GE or O_2-cost at the same submaximal speed compared to XC specialists. Nor did the descriptive comparisons of intra-specialists among elite NC athletes in *Study I* differ in GE or O_2-cost, despite a significant difference in XC performance level. The intra-specialists did, however, differ substantially in body mass and lean upper-body mass with respectively 10 and 5 kg. Coupling these findings with the higher GE found in female cyclists compared to male (Hopker et al. 2010), in an endurance mode where the metabolic work of upper-body is limited, we may speculate that differences in anthropometrics, and in particular upper-body may be an important factor when evaluating group differences in GE. This possible association is something that needs to be investigated in more detail in future studies.

Comparison of annual training to ski jumping and cross-country specialists

NC athletes continuously strive to optimize the concurrent development of two fundamentally different capacities; the rate of force development and net force impulse required for successful SJ performance and the endurance capacity necessary to ski fast in the subsequent XC skiing pursuit. To meet these requirements, world class NC athletes perform the same total of ~850 annual training hours as SJ and XC specialists, but naturally differ to the specialists in the amount of respectively non-endurance and endurance training (*Study II*). Specifically, NC athletes performed approximately half of the SJ specific sessions as SJ specialists, but with a lower average session duration, and two-thirds of the endurance training hours as specialist XC skiers. Thus, that world class NC athletes differed only 10-17% in laboratory capacities to the specialists is noteworthy, and suggest that the training of NC athletes may serve as a successful model for the composition of concurrent strength/power and endurance training.

Training for ski jumping performance

A crucial factor for SJ performance is the ability to produce force rapidly and with a high net force impulse during take-off in the hill. Consequently, training for SJ performance involves strength training across a variety of velocity and resistance loads that primarily affects muscle strength and power with minimal effects on VO_{2max} (Nader 2006). In addition, the complex task of a ski jump requires high body awareness and coordination, flexibility around particularly ankle and hip joints to reach an aerodynamical in-run position, and a high number of technical executions to automate the movements. To achieve all of this, the world class NC athletes in *Study II* composed their training distribution similar to that of the SJ specialists, but with lower average duration per session across training categories. The NC athletes differed, however, with relatively higher emphasis on stretching and less emphasis on dry-land technique training. The greater emphasis on stretching found in the NC athletes is likely a necessity due to negative effect of the endurance training on hip mobility. Following the specificity principle, NC athletes first and foremost prioritize ski jump specific training in the hill when possible (i.e. hill is open for jumping, trainer is available, and weather conditions permits it). Secondly, there is likely a lower limit of repetitions and frequency of strength/power training that is necessary to respectively develop or maintain the vertical jump capacity (Rønnestad 2013), depending on the periodization phase of the season, that needs to be fulfilled. Consequently, the time available for technique training is rapidly declining when compiling the training plan for NC athletes that also involves high amounts of endurance training.

Despite performing approximately half of the strength/power sessions of SJ specialists, the NC athletes in *Study II* differed only 6-7% in general jump capacity (i.e. v_v assessed in CMJ and SQJ, *supplementary data*). This suggest that if any interference effect from endurance training on vertical jump performance exist, world class NC athletes have optimized their training to overcome this negative effect. The greater group difference seen in the sport specific IMIT is thus likely associated with more technique training and ski jumps in SJ specialists enabling them to solve the technical take-off movement more efficiently.

Training for cross-country skiing performance

Endurance training is logically the main focus when the aim is to improve the XC skiing performance of NC. World class XC skiers have previously reported 800-950 annual training hours, using a polarized intensity distribution with high volumes of LIT and low-to-moderate volumes of HIT (Sandbakk 2017; Sandbakk and Holmberg 2014; Solli et al. 2017; Tønnessen et al. 2014). The world class NC athletes investigated in *Studies II-IV* dedicated two-thirds of their annual training to endurance training, and used the same polarized model as found in the abovementioned studies. Consequently, the NC athletes in *Study II* necessarily spent less time in each intensity zone compared to the XC specialists, but with the main difference being less LIT in the classical technique.

The NC athletes and XC specialists investigated in *Study II* both performed similar amount of HIT sessions and time in the skating technique. Several short-term interventions has concluded that HIT induces the physiological adaptations most beneficial to performance (Laursen 2010), and the comparable amount of HIT in the two performance groups is likely an important factor for the high VO_{2peak} values found in the world class NC athletes in *Study I-IV* (i.e. ~72 and ~77 $ml \cdot kg^{-1} \cdot min^{-1}$ in respectively roller-skiing and running) despite moderate amounts of overall endurance training compared to other endurance sports. The 10% lower VO_{2peak} coupled with ~200 less LIT hours in the NC athletes compared to the XC specialists in *Study II* is also in accordance with several other investigations that have indicated that extensive training of this type contributes to the superior aerobic capacity and performance of elite endurance athletes (Sandbakk and Holmberg 2014; Sandbakk et al. 2011b; Solli et al. 2017; Tønnessen et al. 2015a).

Annual training periodization

Previous studies have investigated the annual training periodization of successful world class endurance athletes in e.g. orienteering (Tønnessen et al. 2015b), rowing (Guellich et al. 2009), running (Esteve-Lanao et al. 2005), as well as XC skiing (Solli et al. 2017; Tønnessen et al. 2014). A similar approach was performed in *Study III* where the training of successful world class NC athletes was analyzed in different training phases of the season. In accordance with the above-mentioned studies, the NC athletes reduced their endurance training from GP to CP, primarily by performing less LIT and MIT, while the amount of HIT was maintained. This together with the maintained training frequency across training phases follows a typical tapering pattern described previously in other endurance sports (Bosquet et al. 2007; Mujika and Padilla 2003), where a maintenance of HIT is regarded as sufficient for the development of endurance capacity and the lower overall volume facilitates peak performance.

The novelty of *Study III* was however how successful NC athletes periodize their endurance training in interaction with their non-endurance training. Here, the amount of endurance training was found to be the main manipulator for overall training volume, as the time used for non-endurance training remained relatively stable from GP to CP. Consequently, the proportion of non-endurance training to overall training volume was increased from GP to CP as the endurance training volume was reduced. In the case of NC, this tapering model of endurance training may not only be beneficial for peak XC performance, but also for allowing a greater surplus and quality of the non-endurance training in the same period.

A shift in focus of training was found from GP to SP in both endurance and non-endurance training. For endurance training, there was a gradual decrease in the amount of cross training from TP to SP with corresponding increase in XC-ski training. This is in accordance with earlier studies of XC skiing (Tønnessen et al. 2014) and orienteering (Tønnessen et al. 2015b), where it was suggested that the aim of cross training in the early part of the season is to increase trainability and improve the general aerobic capacity while reducing training monotony. Our data indicate that this also applies for NC athletes.

For the non-endurance training there was an observed shift from TP to CP in both the absolute and relative number of jumps performed in large hills (i.e. 10% of the total number of jumps in GP vs. 18% in CP). In general, the v_v produced at the take-off in small and normal hills has a relatively greater impact on jump distance compared to the large hill, where the longer duration of flight phase makes the aerodynamics relatively more important (Virmavirta et al. 2009). Thus, after working with the initial phases (i.e. in-run and take-off) during GP, the athletes aim to progress to develop transition to flight and flight phase in the large hill in SP and CP.

Although the group of world class NC athletes in *Study III* showed coherent annual periodization patterns, we also observed clear individual differences in the overall training patterns in each training period. The extent to which this is influenced by differences in, for example, physical profiles, training history, or weight regulation needs to be further examined.

Long-term training periodization

In principle, training for sport performance involves applying a physical stress to the body that disrupt homeostasis. If the stress is balanced correctly, a beneficial adaptation to training will increase the body's sustainability to similar stress in subsequent bouts of training. Too much stress, however, without sufficient recovery will increase the chance of overreaching and eventually overtraining. Thus, to reach the training loads of successful world class athletes of ~850 annual training hours, a gradual increase of training volume from early adolescence is necessary. The Olympic champion investigated in *Study IV* performed ~800 annual training hours already at the age of 19 years, with the amount of training sessions equally distributed between non-endurance and endurance training (i.e. 245 non-endurance versus 223 endurance sessions). The amount of non-endurance training sessions was maintained throughout the four-year cycle, whereas the participant progressively increased the amount of endurance training volume, resulting in a total training volume of 1008 hours and 582 sessions in the 2012-13 season before reducing the endurance training by 58 hours in the Olympic season.

Already 20 years old, the participant in *Study IV* had reached a world class vertical jump velocity of ~3.0 $m \cdot s^{-1}$ in CMJ and SQJ. While maintaining his CMJ v_V, despite an increase of 7 kg in body mass, the participant further improved his v_V in sport-specific IMITs by 0.31 $m \cdot s^{-1}$. This improvement coincided with an almost two-fold increase of annual IMITs and a shift in the focus of strength/power exercise. In the 2010-11 season, the participant reported that his strength/power sessions were compiled toward muscle hypertrophy and improving maximal lower-body strength. Thereafter, the sessions were focused more toward high-velocity exercises with more SJ specific movement patterns. This shift of exercise content, with more specificity when the level of strength was sufficient, may have contributed to maintaining his vertical jump capacity parallel with the large increase of endurance training that may induce negative influence on power development (Wilson et al. 2012). In particular, the ~15% increase in IMIT v_V indicates that the execution of this technical skill was not negatively influenced by concurrent endurance training. Overall, it may be beneficial for NC athletes to improve general strength and vertical net force impulse at an early phase of the career when endurance training load is low, followed by a greater focus on high-velocity exercises in a SJ specific movement pattern when increasing the annual endurance load.

With an in-run speed of 23-26 $m \cdot s^{-1}$, SJ and NC athletes rely on an automated and technically optimized take-off pattern for success in the SJ hill. Improved ankle-flexibility and hip/core control enabled the participant in *Study IV* to solve the take-off movement well during dry-land training and testing already early in the Olympic cycle, but it required longer time to transfer this skill to SJ in the hill. Here, systematic mental training to enhance skill acquisition supported the technique training, which was likely a crucial factor for the participant's success at the Olympic Games.

The polarized intensity model and overall endurance volume of ~560 hrs·season^{-1} in the Olympic season is similar to what was seen in other world class NC athletes investigated in *Study II-III*. The amount of endurance training in *Study IV* was, however, increased by an average of 87 hrs·season^{-1} over the initial three seasons, having a peak of 635 hrs·season^{-1}, followed by a reduction in the Olympic season. The adjustment of endurance training load was mainly manipulated by changes in the LIT-zone, with similar amounts of HIT performed in all seasons. This pattern of long-term periodization is similar to what Solli et al. (2017) recently found in the world's best female XC skier. The improvement in VO_{2peak} of ~0.8 L·min^{-1} coupled with the increase of ~200 annual endurance hours observed in *Study IV* further supports the argument made by Solli et al. that such progressive increase in training load may be necessary both for long-term development and for gradually increasing the training-tolerance to sustain the high training doses necessary for world class performance.

The relatively lower endurance load observed in the Olympic season, with a maintained training frequency and amount of HIT compared to the preceding seasons, may indicate that the same tapering strategy observed in the annual training in *Study III* may be beneficial for long-term tapering as well. Perhaps especially so for NC, as the reduced endurance training in the Olympic season may have reduced overall fatigue, and thus improved the quality in the SJ and strength/power sessions, enabling further development of vertical jump velocity in the Olympic season (measured after the 2013-14 season). This may overall suggest that the reduction of endurance training load was beneficial for development of SJ performance in addition to any potential tapering effect on XC performance, and thus, for the enhancing overall NC performance.

Methodological considerations

To date, no studies have validated models to describe training load of the various non-endurance training recorded in this thesis. In general terms, the training volume of endurance and strength training may be calculated as the following;

$$TV_{ENDURANCE} = INTENSITY \cdot TIME \cdot FREQUENCY$$
$$TV_{STRENGTH} = INTENSITY \cdot \sum REPETIONS \cdot FREQUENCY$$

Where the intensity may be measured relative to peak values (e.g. HR_{peak} for running, 1 RM for strength) or in absolute (e.g. $[La^-]_b$ for running, average velocity of movement for strength). The training volume must also be evaluated mode-dependent as different modes of training will load the muscles differently (e.g. XC double-poling vs. running, or squat vs. deadlift). SJ, however, is a complex technical sport that requires mental preparation and extreme focus that causes an additional load that is difficult to measure, quantify, and compare with other types of training. Due to limited validity in the analysis of strength, power, and technique training, successful training patterns in sports where these components are the primary determinants of performance are not well described in the scientific literature. It is also worth noting that these explosive athletes may tolerate and adapt to endurance training somewhat differently than typical endurance athletes examined in previous studies, and may also experience greater muscle loads during strength/power training. These aspects represent challenges that should be considered when interpreting our data.

Naturally, performing laboratory tests involves constraints for direct comparison to outdoor performance in *Study I*. Obvious differences between imitation jumps indoor and hill jumps include the take-off velocity, air resistance, and friction. Similar for XC, the roller skis are shorter than skis and the wheels have different rolling friction and push-off mechanics than skis on snow. However, the purpose of *Study I* was indeed to elucidate the association of laboratory capacities in sport specific movement techniques.

CONCLUSION

This thesis demonstrated how world class NC athletes achieve physical capacities close to the maximum human potential when conducting concurrent strength/power and endurance training to optimize their NC performance. Specifically, world class NC athletes possess a vertical jump capacity of 3 $m \cdot s^{-1}$ combined with VO_{2max} of 77 $ml \cdot kg^{-1} \cdot min^{-1}$. Of the sport-specific capacities obtained in the laboratory, v_v in SJ imitation jump together with body mass were best suited to predict SJ performance in a NC World Cup event, while roller-skiing VO_{2peak} together with upper-body power best predicted XC performance in the same event. These sport-specific capacities were also well-suited to differentiate NC athletes from performance-matched SJ and XC specialists. However, world class NC athletes differed only 10-17% in these capacities compared to the SJ and XC specialists, who train close to twice the amount of respectively technique training and low-intensity training than NC athletes.

World class NC athletes train on both ends of the strength-endurance continuum by balancing their 800-1000 annual training hours as two-thirds of endurance and one-third SJ specific training (i.e. ski jumps, dry land technique training, strength/power, motor control, and stretching). The training is performed using a similar distribution model to that of the specialists, but where NC athletes on average use shorter session durations and limited time in the classical technique. Following the specificity principle, NC athletes prioritize specific training with a high relative emphasis on SJ sessions and high-intensity endurance training using skating technique on roller skis or skis. Across the annual cycle, relatively more emphasis is put on specific training from the initial training phases towards the competition phase.

Both for annual periodization in a group of NC athletes and long-term training periodization in an Olympic champion in NC, low-intensity endurance training was found to be the main manipulator of overall training volume as the amount of SJ specific training and high-intensity endurance training is maintained relatively stable. For long-term periodization from youth to adolescence, data from a multi-winning Olympic NC Champion indicate that it is advisable to focus on increasing lower-body muscle strength and vertical jump impulse in youth years when the amount of endurance training is low-to-moderate. Thereafter the emphasis should be placed on utilizing the acquired capacity in the more technical execution of take-off movement as endurance training volume is progressively increased to enhance XC skiing performance further, mainly by a manipulation of low-intensity training.

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Study I

Study I

PLOS ONE

RESEARCH ARTICLE

Association between laboratory capacities and world-cup performance in Nordic combined

Vegard Rasdal[1]*, Ronny Fudel[2], Jan Kocbach[1], Frode Moen[1,3], Gertjan Ettema[1], Øyvind Sandbakk[1]

1 Centre for Elite Sports Research, Department of Neuromedicine and Movement Science, Factulty of Medicine and Health Science, Norwegian University of Science and Technology, Trondheim, Norway, **2** Institute of Movement and Training Science in Sports, Faculty of Sport Science, Leipzig University, Leipzig, Germany, **3** Department of Education, Norwegian University of Science and Technology, Trondheim, Norway

* vegard.rasdal@ntnu.no

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Data Availability Statement: Relevant analyses and data are included in the manuscript. However, we could not make raw data publicly available for the reader since this could compromise participant confidentiality. In order to achieve approval from The Norwegian Data Protection Authority, we had to ensure participant confidentiality. By providing raw data publicly available for the reader, the competition data in this study could easily be traced to full athlete names in FIS' public available world cup competition results, and thus be a breach of this confidentiality. For access to raw

Abstract

Background

Nordic combined (NC) is an Olympic winter-sport performed as a ski jumping (SJ) event followed by a cross-country (XC) pursuit race employing the skating style.

Purpose

To elucidate the associations between sport-specific laboratory capacities and SJ, XC skiing, and overall NC performance in a world-cup NC event.

Methods

Twelve international world-cup NC athletes from 8 nations performed laboratory testing one day prior to participating in a world-cup NC event. Squat jumps and SJ imitations (IMIT) were performed on a three-dimensional force plate, whereas XC skiing-specific physiological characteristics were obtained from roller ski skating tests on a treadmill and an all-out double poling (DP) test. Finally, body composition was measured. Laboratory capacities were correlated against performance in SJ, 10-km XC skiing, and overall NC in the world-cup event. Multiple regression analysis was used to determine the best suited laboratory variables for predicting performance.

Results

Vertical IMIT velocity together with body-mass provided the best prediction for SJ performance ($r^2 = 0.70$, $p<0.01$), while body-mass-normalized $\dot{V}O_{2peak}$ and DP power provided the best prediction for XC performance ($r^2 = 0.68$, $p<0.05$). Body-mass-normalized $\dot{V}O_{2peak}$ was the only significant correlate with overall NC performance ($r^2 = 0.43$, $p<0.05$) in this competition.

data, send your request to The Norwegian Data Protection Authority (nsd@nsd.no).

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Conclusion

Overall, the concurrent development of $\dot{V}O_{2peak}$, upper-body power, and SJ-specific vertical jump capacity while minimizing body-mass within the BMI limit set by FIS should be considered in the seasonal training of NC athletes.

Introduction

Nordic combined (NC) is a traditional Olympic winter-sport, and is performed as a ski jumping (SJ) event followed by a cross-country (XC) pursuit race employing the skating style over a distance of 5–15 km (standard competition is 10 km). Both events are carried out on the same day with 1–3 hours in between, where each athlete starts the XC race with a time disadvantage per point lost to the winner of the SJ event. Consequently, NC athletes need to perform well in two fundamentally different sports; SJ that requires well-developed explosiveness and jumping technique and XC skiing where aerobic energy delivery and skiing efficiency are key determinants [1–4].

Of the different phases of a ski jump (i.e. in-run, take-off, flight phase, landing), the take-off is regarded as the most crucial for performance due to its influence on the initial vertical velocity of the flight and the maintenance of high horizontal velocity in the early flight phase [1, 2, 5]. In successful ski jumpers, a high vertical jump ability and a low body-mass are well-established characteristics [1, 2, 6, 7]. These characteristics also differentiates NC athletes from specialist ski jumpers [8, 9]. However, no research to date have investigated associations between sport-specific laboratory capacities and field performance in SJ among NC athletes that concurrently develop their aerobic capacity and upper-body power.

XC skiing races are performed in varied terrain and more than 50% of the racing time is normally spent in uphill terrain, which also constitutes the most performance-differentiating terrain [3, 10–12]. Accordingly, XC skiers have possessed some of the highest maximal oxygen uptake ($\dot{V}O_{2max}$) values ever reported [3, 13–16]. Following the higher maximal aerobic capacity, better skiers also endure lower physiological stress, ski more efficiently, and produce longer cycle lengths at submaximal speeds than lower-level skiers [4, 17, 18]. In addition, more focus in recent literature has been placed on the importance of upper-body power for XC performance [17, 19, 20]. The significance of these factors for performance in NC events, however, has not been investigated. Since NC athletes may compensate lower XC skiing level with better SJ performance, they present a more heterogeneous group of endurance athletes than XC skiers [8].

The aim of this study was to elucidate the associations between sport-specific laboratory capacities and performance in SJ, XC skiing, and overall NC in a world-cup event among international NC athletes. Our major hypotheses were that $\dot{V}O_{2peak}$ and vertical velocity achieved during ski jump imitations were the main correlates of overall NC performance, with upper-body power and body-mass being additional correlates of XC skiing and SJ performance, respectively. A secondary purpose of the study was also to provide benchmark values of laboratory capacities of world-class athletes in NC.

Materials and methods

The study was approved by The Norwegian Data protection Authority. All participants signed an informed consent from before the experiment and were made aware that they could withdraw from the study at any point without providing an explanation. The study was conducted in accordance with the Declaration of Helsinki.

Participants

Twelve international world-cup NC athletes from 8 nations volunteered to participate in the study. The participants´ age, anthropometrics, body composition, and performance level in SJ, XC skiing, and overall world-cup standing at the time of the study, classified according to the system proposed by the International Ski Federation (FIS) (www.fis-ski.com), are depicted in Table 1.

Overall design

The athletes performed a set of laboratory tests one day prior to participating in a world-cup event. SJ imitations (IMIT), and squat jumps (SQJ) to measure true vertical jump capacity, were performed on a three-dimensional force plate, whereas XC skiing-specific characteristics were obtained from submaximal and maximal roller ski tests in G2 skating on a treadmill as described in detail in a previous study [21]. In addition, body composition was determined and a 30-sec all-out double poling (DP) test was performed on a DP ergometer as a measure for upper-body power capacity. Laboratory capacities and selected anthropometrics were correlated against performance in SJ, XC, and overall NC in the subsequent world-cup competition. In addition, benchmark values of laboratory capacities and selected anthropometrics are presented for the top 3 ranked SJ (SJ_{top3}) and XC skiers (XC_{top3}) in the group, based on their FIS ranking. These two performance groups did not overlap.

Methodology

To measure the magnitude and direction of forces during SQJ and IMIT jumps, two Kistler force platforms (Kistler 9286AA, Kistler Instrument Corp, Winterthur, Switzerland) were set

Table 1. Anthropometrics, body composition, and FIS ranking/world-cup standing of the twelve international Nordic combined world-cup athletes and benchmark values for subgroups of the top 3 FIS ranked athletes in cross-country skiing (XC_{top3}) and ski jumping (SJ_{top3}). All variables are presented as mean ± SD (range) for each group.

Variable	All (n = 12)	XC_{top3} (n = 3)	SJ_{top3} (n = 3)
Age (yr)	24.1 ± 3.7 (18–30)	27.3 ± 3.1 (24–30)	23.7 ± 2.1 (22–26)
Body height (cm)	178.4 ± 6.0 (170–187)	180.5 ± 5.41 (174.5–185)	172.8 ± 3.82 (169.5–177)
Body mass (kg)	65.8 ± 6.3 (56.5–73.1)	69.2 ± 4.42 (64.1–72.2)	59.4 ± 3.67 (56.5–63.5)
Body mass index ($kg \cdot m^{-2}$)	20.6 ± 0.8 (19.3–22.1)	21.2 ± 0.24 (21.1–21.5)	19.9 ± 0.36 (19.6–20.3)
Fat mass (kg)	4.2 ± 1.2 (2.3–6.7)	4.9 ± 1.57 (3.8–6.7)	3.3 ± 1.0 (2.3–4.3)
Fat mass (%)	6.3 ± 1.5 (4.0–9.3)	7.0 ± 1.9 (5.9–9.3)	5.6 ± 1.8 (4.0–7.6)
LM upper-body (kg)	33.8 ± 3.3 (27.9–38.3)	35.0 ± 2.24 (32.6–37.0)	30.5 ± 2.70 (27.9–33.3)
LM upper-body (%)	51.4 ± 1.2 (48.9–52.8)	50.6 ± 1.5 (48.9–52.0)	51.4 ± 1.7 (49.4–52.4)
LM lower-body (kg)	19.4 ± 2.1 (16.4–21.9)	20.4 ± 1.77 (18.4–21.8)	17.7 ± 1.33 (16.4–19.0)
LM lower-body (%)	29.5 ± 0.7 (28.2–30.4)	29.4 ± 0.8 (28.7–30.2)	29.8 ± 0.7 (29.0–30.4)
FIS rank ski jumping[1]	6.5 ± 1.75 (4–9)	5.0 ± 1.0 (4–6)	8.7 ± 0.58 (8–9)
FIS rank cross-country[1]	6.9 ± 2.26 (3–10)	9.3 ± 0.58 (9–10)	6.0 ± 2.0 (4–8)
FIS WC standing[2]	29.5 ± 20.3 (2–66)	15.7 ± 9.3 (8–26)	17.3 ± 15.0 (2–32)

LM = lean mass; FIS = International ski federation

[1] FIS ranking between 1–10 based on respectively ski jumping and cross-country skiing performance in Nordic combined world cup events where 10 is highest performance level.

[2] FIS World cup leaderboard standing in the 2013/2014 season prior to the study. Lower number is better.

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up in series, so the athletes could place the forefoot on one platform and the rear foot on the other while performing a jump. As the ski-athlete system with bindings and SJ boots limits the plantar flexion at take-off in the hill, this setup was performed to allow for performance measures when the whole foot is in contact with the force plate during IMIT push-offs.

All treadmill tests were performed on a 5x3 m motor-driven treadmill (Forcelink B.V., Culemborg, The Netherlands) and the skiers used their own poles (90±1% of body height) using special carbide tips. All subjects were secured to the roof with a safety harness during testing. To minimize roller resistance variation, all subjects used the same pair of skating roller skis with standard wheels (IDT Sports, Lena, Norway). Before the tests, the roller skis were pre-warmed by 20 minutes of roller skiing on the treadmill and tested for rolling friction force (F_f) with the towing test as previously described [4]. Skating kinematics were measured by seven Oqus infrared cameras operating at 250 Hz and Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden) using two reflective markers placed on the lateral side of the carbide tip of both poles.

Respiratory variables were measured using open-circuit indirect calorimetry (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany) with calibration procedures presented previously [8]. Heart rate was continuously measured with a Polar V800 monitor (Polar Electro Oy, Kempele, Finland) and synchronized with the Oxycon Pro measurement system. Blood lactate concentration in 20 μL of blood taken from each skier's fingertip was measured using the Biosen C-Line lactate analyser (Biosen, EKF Industrial Electronics, Magdeburg, Germany). Rating of perceived exertion (RPE) was assessed using the Borg Scale [22].

DP was performed on a modified Concept2 SkiErg (Morrisville, VT, USA) as described elsewhere [19]. Power output and cycle rate were continuously measured by the ergometer´s internal software, which has been validated in previous studies [19, 23].

Body height was determined using a calibrated stadiometer (Holtain Ltd, Crosswell, UK). Body-mass and body composition was measured using a multifrequency impedance plethysmograph body composition analyser (InBody 720, Biospace, Korea), and performed in accordance with the company´s guidelines for testing. The participants were weighed and scanned in their underwear and without shoes prior to warm-up and testing.

Valid course and elevation profiles of the XC course were standardized with a Polar V800 GPS that collected position data at a 1 Hz sampling rate with integrated barometry that collected accurate elevation data. The course was then based on the course profile divided into uphill, flat, and downhill sections that made up 40%, 5%, and 55% of the 2 km lap, respectively (Fig 1). The different sections were defined as described in a previous study [10].

During the XC race, each participant wore a Polar V800 that continuously measured their position at a 1 Hz sampling rate. All GPS watches were turned on more than 30 minutes before the race start to ensure proper GPS fixing and a low resultant inaccuracy in GPS data.

Test protocols and measurements

The squat jump and ski jump imitation. Two SQJs and four IMITs were performed with the athletes´ personal jumping boots with the forefoot and rear foot placed in a standardized position on the force plates. All jumps were performed with maximal effort, and a break of 2–5 minutes between the jumps. The athletes scored each jump on a scale from 0–10, where 10 represented a perfectly executed jump. The jump with the highest rating was used for further analysis. The SQJ was performed from a stationary squat position with the hands located on the iliac crest throughout the jump, as described in a previous study [24]. The IMIT was performed from the athletes' individually chosen ski jump position, and after maintaining this position in a static fashion for at least one second the athletes aimed to maximize their vertical lift but simultaneously gain sufficient angular momentum in order to end up in a flight-phase

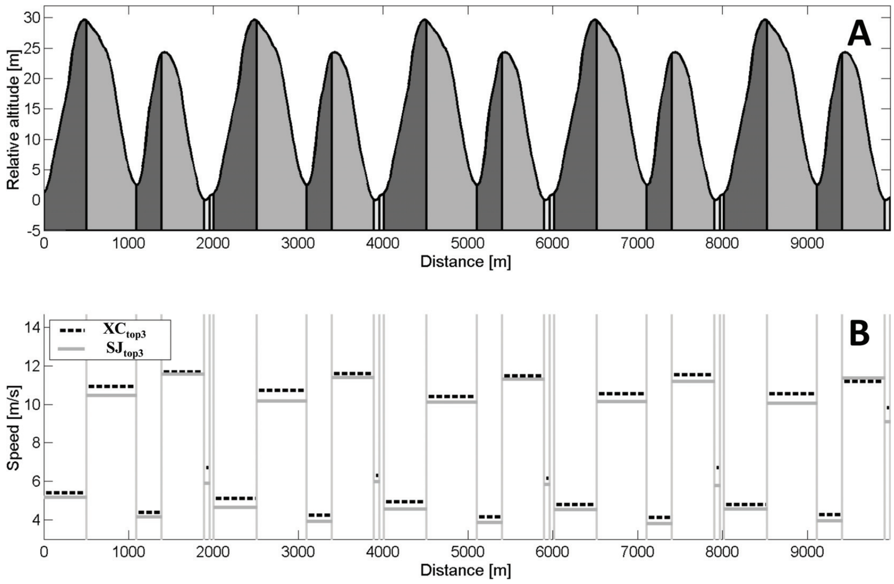

Fig 1. 10 km race course profile with average speeds in each segment. The upper graph (A) represents the racecourse profile of the 10 km cross-country race with the relative elevation with regard to zero (start) and uphill, flat, and downhill sections in different tones of gray. The lower graph (B) represents the average speed (m·s^{-1}) in the defined sections for both the top 3 ranked cross-country skiers (XC_{top3} in black stapled lines) and the top 3 ranked ski jumpers (SJ_{top3} in gray solid lines).

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position to be caught by their coach, as described in a previous study [8]. The concentric push-off phase was defined as the time period of upward movement. During this phase, the vertical velocity of the centre of mass was determined by the integration of acceleration over time, which was calculated by dividing the vertical ground-reaction force with body-mass. For the IMIT, the vertical velocity was calculated at the instant of heel lift-off from the force plate (Vv_{BIMIT}) as well as for maximum achieved vertical velocity (Vv_{IMIT}), while only the maximum achieved vertical velocity was used for the squat jump (Vv_{SQJ}). The centre of mass position was obtained through double integration of acceleration, both in horizontal and vertical directions. Ground reaction force and the position of centre of mass allowed for the calculation of angular momentum in the IMIT, which was determined both at the instant of heel lift-off (L_{BIMIT}) and for the instant at maximum achieved vertical velocity (L_{IMIT}).

The submaximal roller ski test. All athletes performed ten minutes of familiarization to the treadmill followed by one submaximal five-minute stage of treadmill skiing at 12% inclination and 7 km·h^{-1} to compare physiological response and gross efficiency. Gas exchange and heart rate were determined by the average of the last minute, and blood lactate concentration was measured directly after completion. Power output was calculated as the sum of power against gravity and friction as described previously [8]. The metabolic rate was calculated from $\dot{V}O_2$ and $\dot{V}CO_2$, as the product of $\dot{V}O_2$ and the oxygen energetic equivalent using the associated respiratory exchange ratio and standard conversion tables [25]. Gross efficiency was then calculated as the power output divided by the metabolic rate, and presented as a percentage.

The maximal roller ski test. The $\dot{V}O_{2peak}$ test at 12% inclination had an initial speed of 8 km·h^{-1}, which was increased by 1 km·h^{-1} every minute until exhaustion, and the highest speed maintained for at least 30 seconds was used as peak speed. $\dot{V}O_2$ was measured continuously, with the $\dot{V}O_{2peak}$ determined by the average of the three highest 10-second consecutive measurements and according to previously determined criteria for achieving maximal effort [8]. Post-exercise blood lactate was measured one and three minutes after the test, and the highest value was used for analysis.

Measurements of skating kinematics. Skating kinematics were collected from the five-minute submaximal work load and the highest work load that all athletes completed during the incremental test by using Oqus infrared cameras and reflective markers on both poles. Cycle length was determined by multiplying cycle time with the belt speed of the treadmill, whereas cycle rate was calculated as the reciprocal of cycle time. Kinematical variables were collected and averaged for each athlete over 10 consecutive cycles using definitions presented previously [8].

Double poling all-out test. The athletes were placed in a standardized distance from a wall-mounted Concept2 ergometer, and performed the test using training shoes. The 30-s test started when the athlete performed his first pull. All athletes were instructed to double pole with full effort during the whole 30-s period.

Competition results. Official competition results were collected from the FIS web page (www.fis-ski.com). The hill-size of the SJ event was K-124 m where each meter jumped above or below 124 m is multiplied with 1.5 points and respectively added or subtracted from 60 pts. The total SJ pts in a competition is a summation of distance points, compensation points for wind conditions and changes in starting gate, and judges' style points. SJ performance was defined as the sum of length points and gate/wind compensation points, thus excluding the judges´ style points to enable a better comparison with the laboratory tests. The XC performance was defined as the 10-km race time, while overall NC performance was defined as the overall competition rank in the world cup event.

The weather during the SJ event was partly cloudy with 68% humidity, air and snow temperature of respectively 2.3˚C and 6.5˚C, and wind conditions from 0.84 $m \cdot s^{-1}$ tail wind to 0.39 $m \cdot s^{-1}$ head wind. The average wind condition for the event was 0.23 $m \cdot s^{-1}$ tail wind. For the XC event, the air and snow temperature was respectively 1.8˚ and -2.1˚Celsius with hard snow conditions.

Statistical analysis

All data were tested for a normal distribution using a Shapiro-Wilk test as well as by visual inspection, and are presented as mean±SD (range). Accordingly, correlation analysis between laboratory and field performance was conducted using the parametric Pearson´s r or the non-parametric Spearman´s ρ correlation coefficient. Multiple regression analyses using enter-method with blocks of 1–2 independent variables were employed to predict performance in XC, SJ, and overall NC. An alpha value of 0.05 was used as the level of statistical significance. All statistical analyses were performed using SPSS 24.0 Software for Windows (SPSS Inc, Chicago, IL). To provide benchmark values of high level SJ and XC skiers among the 12 athletes participating in this study, the top 3 ranked athletes for each performance group are descriptively presented.

Results

Body composition and laboratory capacities

Anthropometrics and body composition for all athletes and the two performance groups are presented in Table 1, while sport-specific laboratory capacities for SJ and XC skiing are presented in Tables 2 and 3.

Competition results

Competition results for all athletes and the two performance groups are presented in Table 4. All 6 athletes in SJ_{top3} and XC_{top3} finished in top 7 of the athletes recruited to this study. Although they differed substantially in their XC and SJ performance, the mean overall ranking and time difference to the winner of the NC competition was close to identical.

Correlation and regression analysis

Correlations between laboratory variables and XC, SJ, and overall performance are listed in Table 5, while the most central associations are presented in Fig 2. For the specific sections, time spent uphill correlated significant with body-mass-normalized $\dot{V}O_{2peak}$ (r = -0.633, p = 0.027).

The regression analyses, with the various laboratory capacities and anthropometric characteristics as independent variables, resulted in the following three equations as the best predictions for SJ (I), XC (II), and overall (III) performance respectively.

$$\text{SJ performance} = 8.51 + 35.90 \cdot \text{Vv}_{\text{IMIT}}\ (\text{m} \cdot \text{s}^{-1}) - 0.58 \cdot \text{body} - \text{mass (kg)} \quad (\text{F}_{2,9} = 10.41,\ \text{p} < 0.01) \tag{I}$$

The factors included in Eq (I) all significantly contributed to model I (all p<0.05) which explained 70% of the variance in SJ performance.

$$\text{XC performance} = 40.29 - 0.12 \cdot \dot{V}\text{O}_{2\text{peak}}\ (\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) - 0.64 \cdot \text{DP power}\ (\text{W} \cdot \text{UBLM}^{-1}) \quad (\text{F}_{2,8} = 8.63, \text{p} = 0.01) \tag{II}$$

$\dot{V}O_{2peak}$ significantly contributed to model II (p<0.05), while DP power showed a tendency (p = 0.07). Model II explained 68% of the variance in XC performance.

$$\text{Overall performance} = 156.45 - 1.75 \cdot \dot{V}\text{O}_{2\text{peak}}\ (\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) \quad (\text{F}_{1,10} = 7.47,\ \text{p} = 0.02) \tag{III}$$

Model III explained 43% of the variance in overall performance.

Discussion

The present study investigated associations between sport-specific laboratory capacities and NC world-cup performance in NC athletes who combine well-developed explosiveness and SJ

Table 2. Sport-specific capacities based on a squat jump (SQJ) and a simulated ski jump (IMIT) performed on a 3D force plate for the twelve international Nordic combined world-cup athletes and subgroups of the top 3 FIS ranked cross-country skiers (XC_{top3}) and ski jumpers (SJ_{top3}). All variables are presented as mean ± SD (range) for each group.

Variable	All (n = 12)	XC_{top3} (n = 3)	SJ_{top3} (n = 3)
Vv_{SQJ} (m·s^{-1})	2.73 ± 0.11 (2.60–2.92)	2.70 ± 0.05 (2.66–2.75)	2.84 ± 0.13 (2.69–2.92)
$Time_{IMIT}$ (s)	0.41 ± 0.04 (0.30–0.46)	0.44 ± 0.03 (0.41–0.46)	0.36 ± 0.05 (0.30–0.39)
Vv_{IMIT} (m·s^{-1})	2.41 ± 0.16 (2.11–2.67)	2.25 ± 0.15 (2.11–2.40)	2.54 ± 0.13 (2.40–2.66)
VvB_{IMIT} (m·s^{-1})	1.84 ± 0.63 (0.00–2.39)	1.97 ± 0.22 (1.72–2.14)	2.15 ± 0.33 (1.77–2.39)
L_{IMIT} (N·m·s)	14.3 ± 4.1 (8.7–23.3)	15.2 ± 7.4 (8.7–23.3)	15.7 ± 2.2 (13.3–17.5)
LB_{IMIT} (N·m·s)	12.0 ± 6.5 (-3.0–22.6)	14.3 ± 7.9 (6.8–22.6)	14.6 ± 2.1 (12.3–16.5)

Vv_{SQJ} = maximum achieved vertical velocity of the skier in squat jump; $Time_{IMIT}$ = time of push-off in the imitation jump; Vv_{IMIT} = maximum achieved vertical velocity of the skier in imitation jump; VvB_{IMIT} = vertical velocity at the instant of heel lift-off in imitation jump; L_{IMIT} = the angular momentum at the instant of maximum achieved vertical velocity in the imitation jump; LB_{IMIT} = the angular momentum at the instant of heel lift-off in the imitation jump.

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Table 3. Physiological responses, gross efficiency, and cycle characteristics while roller ski skating at submaximal (i.e., 7 km·h^{-1}) and stepwise incremental intensity to exhaustion (i.e., 12 km·h^{-1} and peak speed) on a 12% incline and performance measures of 30-seconds all-out double poling in the twelve international Nordic combined world-cup athletes and subgroups of the top 3 FIS ranked cross-country skiers (XC_{top3}) and ski jumpers (SJ_{top3}). All variables are presented as mean ± SD (range) for each group.

Variable	All (n = 12)	XC_{top3} (n = 3)	SJ_{top3} (n = 3)
7 km·h^{-1}			
$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	50.0 ± 1.8 (47.5–53.7)	48.9 ± 1.0 (47.8–49.7)	49.0 ± 1.6 (57.5–50.6)
$\dot{V}O_2$ (L·min^{-1})	3.29 ± 0.31 (2.68–3.73)	3.38 ± 0.20 (3.16–3.54)	2.91 ± 0.27 (2.68–3.21)
$\dot{V}O_2$ in % of $\dot{V}O_{2peak}$	68.2 ± 4.2 (61.5–75.4)	63.9 ± 2.4 (62–66)	67.2 ± 3.1 (65–71)
HR in % of HR_{peak}	80.9 ± 5.2 (72–90)	77.0 ± 5.0 (72–81)	80.8 ± 4.5 (76–85)
RER	0.90 ± 0.05 (0.82–0.98)	0.89 ± 0.03 (0.86–0.92)	0.93 ± 0.04 (0.89–0.97)
BLa (mmol·L^{-1})	2.5 ± 0.6 (1.6–3.4)	2.1 ± 0.1 (2.0–2.2)	2.6 ± 0.3 (2.2–2.8)
GE (%)	16.2 ± 0.5 (15.4–16.9)	16.6 ± 0.3 (16.3–16.8)	16.4 ± 0.5 (16.0–16.9)
RPE (6–20)	11.9 ± 1.38 (10–14)	13.0 ± 0.0 (13)	11.3 ± 1.5 (10–13)
Cycle length (m)	2.79 ± 0.18 (2.51–3.04)	2.88 ± 0.14 (2.76–3.04)	2.72 ± 0.18 (2.55–2.91)
Cycle rate (Hz)	0.70 ± 0.05 (0.64–0.77)	0.68 ± 0.04 (0.64–0.71)	0.72 ± 0.05 (0.67–0.76)
12[a] km·h^{-1}			
Cycle length (m)	3.96 ± 0.37 (3.0–4.3)	3.99 ± 0.12 (3.87–4.11)	3.92 ± 0.35 (3.60–4.29)
Cycle rate (Hz)	0.85 ± 0.09 (0.77–1.10)	0.84 ± 0.03 (0.81–0.86)	0.85 ± 0.07 (0.78–0.93)
Peak speed			
Peak speed (km·h^{-1})	12.9 ± 0.5 (12–14)	13.3 ± 0.6 (13–14)	13.0 ± 0.0 (13)
$\dot{V}O_{2peak}$ (ml·kg^{-1}·min^{-1})	73.5 ± 4.3 (66.9–80.8)	76.6 ± 4.4 (72.1–80.8)	73.0 ± 1.5 (71.5–74.5)
$\dot{V}O_{2peak}$ (L·min^{-1})	4.83 ± 0.50 (4.12–5.75)	5.30 ± 0.42 (4.94–5.75)	4.33 ± 0.21 (4.12–4.54)
Peak RER	1.17 ± 0.06 (1.03–1.25)	1.18 ± 0.00 (1.18)	1.18 ± 0.05 (1.15–1.23)
Peak VE (L·min^{-1})	157.0 ± 11.6 (133–172)	157.3 ± 5.1 (153–163)	155.3 ± 13.6 (140–166)
Peak bLa (mmol·L^{-1})	13.1 ± 1.6 (10.2–15.2)	13.9 ± 0.8 (13.4–14.8)	12.9 ± 0.7 (12.3–13.7)
30-s all out DP exercise			
Mean power output			
(W)	323 ± 46 (233–379)	344 ± 39 (316–371)	285 ± 55 (233–343)
(W·kg^{-1})	4.9 ± 0.4 (4.1–5.6)	5.1 ± 0.2 (4.9–5.2)	4.8 ± 0.6 (4.1–5.4)
(W·LM^{-1})	5.3 ± 0.4 (4.5–6.0)	5.4 ± 0.2 (5.2–5.5)	5.1 ± 0.6 (4.5–5.7)
(W·UB LM^{-1})	9.6 ± 0.7 (8.4–10.7)	9.9 ± 0.2 (9.7–10.0)	9.3 ± 1.0 (8.4–10.3)
Mean cycle rate (Hz)	1.38 ± 0.15 (1.18–1.63)	1.33 ± 0.07 (1.28–1.38)	1.59 ± 0.06 (1.52–1.63)

$\dot{V}O_2$ = oxygen uptake; HR = heart rate; RER = respiratory exchange ratio; BLa = blood lactate concentration; GE = gross efficiency; RPE = rating of perceived exertion; $\dot{V}O_{2peak}$ = peak oxygen uptake from incremental test to exhaustion; VE = ventilation.

[a] 12 km·h^{-1} was the highest speed completed by all 12 athletes in the incremental test.

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technique with aerobic energy delivery capacity and XC skiing efficiency. Our main findings were as following: 1) vertical velocity obtained in an imitation jump (Vv_{IMIT}) and body-mass provided the best prediction of SJ performance; 2) body-mass-normalized $\dot{V}O_{2peak}$ and double poling (DP) power provided the best prediction of XC performance; 3) body-mass-normalized $\dot{V}O_{2peak}$ was the only significant correlate with overall NC performance. In addition, the benchmark values provided for the best performing athletes in SJ and XC skiing among NC athletes further support the importance of these factors for the specific events.

SJ performance correlated significantly with both Vv_{IMIT} and $time_{IMIT}$, while Vv_{IMIT} together with body-mass were best suited to predict SJ performance. These findings are in

Table 4. Ski jumping (SJ), cross-country (XC) skiing, and overall result of the world-cup event, with the percentage of the total XC race time spent in uphill, flat, and downhill sections, in twelve international Nordic combined world-cup athletes (n = 12) and subgroups of the top 3 FIS ranked athletes in cross-country skiing (XC_{top3}) and ski jumping (SJ_{top3}). All variables are presented as mean ± SD (range) for each group.

Variable	All (n = 12)	XC_{top3} (n = 3)	SJ_{top3} (n = 3)
SJ result			
Points	57.2 ± 8.3 (46.7–70.0)	49.2 ± 1.37 (48.0–50.7)	67.4 ± 2.4 (65.3–70.0)
Rank	29.5 ± 13.9 (5–45)	41.7 ± 2.5 (39–44)	11.3 ± 6.5 (5–18)
XC result			
Minutes	25.00 ± 1.07 (23.55–27.08)	23.81 ± 0.30 (23.55–24.13)	25.24 ± 0.61 (24.57–25.77)
% uphill	60.8 ± 0.9 (59.5–62.2)	60.1 ± 0.6 (59.5–60.6)	60.8 ± 0.7 (59.9–61.3)
% flat	4.1 ± 0.2 (3.9–4.4)	4.1 ± 0.1 (3.9–4.2)	4.3 ± 0.2 (4.1–4.4)
% downhill	33.8 ± 0.8 (32.6–35.2)	34.6 ± 0.6 (34.0–35.2)	33.5 ± 0.3 (33.3–33.8)
Rank	23.0 ± 16.7 (1–45)	3.3 ± 3.2 (1–7)	28.0 ± 13.5 (13–39)
Overall result			
Minutes	26.39 ± 0.94 (24.96–28.54)	25.82 ± 0.20 (25.62–26.01)	25.74 ± 0.68 (24.96–26.20)
Rank	28.0 ± 11.5 (7–45)	19.7 ± 5.5 (14–25)	20.0 ± 11.3 (7–27)

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accordance with established performance characteristics of successful ski jumpers, where the ability to reach maximal vertical velocity in a very short time (<0.35 s) is necessary for a successful take-off [2, 5]. This is, however, the first study to show that the same variables correlate to SJ performance in NC, where NC athletes possess some different challenges than specialist ski jumpers. The time available at the take-off in the SJ hill may present a greater challenge for NC athletes than specialist ski jumpers as two-thirds of the NC athletes' annual training consists of endurance training [8, 24]. This does not only leave less time available for power and SJ specific training compared to the specialists, but endurance training may lead to negative effects on muscle strength and power [26, 27]. This might partly explain the correlation found between Vv_{IMIT} or $time_{IMIT}$ with XC performance. Furthermore, the lack of association between Vv_{SQJ} and SJ performance suggests that the maximum vertical velocity achieved in the technically challenging task of an IMIT is more relevant for SJ performance than the pure vertical jump capacity assessed by SQJ.

Although body-mass coupled with Vv_{IMIT} gave the best prediction of SJ performance, neither body-mass nor BMI alone showed a significant correlation with SJ performance. This lack of association, however, might be influenced by the two-sided effect of body-mass. While a lower body-mass will reduce the effect of gravity during the flight phase, and hence have a positive impact on performance, it will also reduce the positive effect of gravity on in-run speed and the horizontal momentum at take-off [5]. Yet, a low body-mass has been found to have an overall positive effect on SJ performance in simulation studies [5, 28], in addition to being beneficial for maximizing vertical velocity at take-off. Hence, the overall assessment is that low body-mass is a contributing factor for SJ performance. This is also in agreement with a low body-mass being a performance characteristic found among successful ski jumpers [8, 9].

As expected, body-mass-normalized $\dot{V}O_{2peak}$ and DP power were the best predictors for XC performance. The importance of a high aerobic capacity is well established in several endurance sports, including XC skiing [3, 16], but this is the first study to validate the association to competitive performance among elite NC athletes. The importance of upper-body power for XC performance is repeatedly shown in recent XC skiing literature [17, 20, 23, 29, 30]. The finding that DP power significantly correlated with XC performance in this study was therefore no surprise. In our case, the highest correlation was when normalizing power for upper-

Table 5. Pearson's r or Spearman's ρ correlations between field performance and laboratory capacities in twelve international Nordic combined world-cup athletes.

	XC performance (time)	SJ performance (pts)	Overall performance (rank)
Field performance (n = 12)			
Time uphill	**.980[#] (p<0.001)**		
Time downhill	**.847[#] (p<0.001)**		
Time flat	**.774[#] (p<0.001)**		
XC performance		.565 (p = 0.055)	**.757[#] (p = 0.004)**
SJ performance	.565 (p = 0.055)		-.013 (p = 0.967)
SJ in-run speed (km·h^{-1})		.200 (p = 0.533)	.064 (p = 0.844)
SJ specific variables (n = 12)			
Body mass (kg)	-.119[a] (p = 0.712)	-.511[a] (p = 0.089)	.270[a] (p = 0.397)
Body mass index (kg·m^{-2})	-.481 (p = 0.113)	-.426 (p = 0.168)	-.052 (p = 0.872)
Vv_{SQJ} (m·s^{-1})	.237 (p = 0.458)	.528 (p = 0.078)	.042 (p = 0.897)
$Time_{IMIT}$ (s)	**-.605[a]* (p = 0.037)**	**-.763[a#] (p = 0.004)**	-.186 (p = 0.562)
Vv_{IMIT} (m·s^{-1})	.525 (p = 0.080)	**.711* (p = 0.010)**	.238 (p = 0.456)
VvB_{IMIT} (m·s^{-1})	.224[a] (p = 0.484)	.329[a] (p = 0.297)	-.035[a] (p = 0.914)
XC specific variables (n = 12)			
$\dot{V}O_{2peak}$ (L·min^{-1})	-.511 (p = 0.090)	-.519 (p = 0.084)	-.164 (p = 0.611)
$\dot{V}O_{2peak}$ (ml·kg^{-1}·min^{-1})	**-.619* (p = 0.032)**	-.192 (p = 0.550)	**-.654* (p = 0.021)**
DP power (W)	-.389 (p = 0.237)	-.563 (p = 0.072)	.074 (p = 0.829)
DP power (W·kg^{-1})	**-.608* (p = 0.047)**	-.548 (p = 0.081)	-.243 (p = 0.472)
DP power (W·LM^{-1})	**-.607* (p = 0.048)**	**-.617* (p = 0.043)**	-.178 (p = 0.602)
DP power (W·UB LM^{-1})	**-.671* (p = 0.024)**	-.568 (p = 0.069)	-.253 (p = 0.452)
GE 7 km/h (%)	-.315 (p = 0.319)	-.081 (p = 0.802)	-.305 (p = 0.335)
CL 7 km/h (m)	-.194 (p = 0.545)	-.427 (p = 0.167)	-.008 (p = 0.980)
CL 12 km/h (m)	-.084[a] (p = 0.795)	-.266[a] (p = 0.404)	.350[a] (p = 0.265)

XC = cross-country; SJ = ski jumping; Vv_{SQJ} = maximum achieved vertical velocity of the skier in squat jump; $Time_{IMIT}$ = time of push-off in the imitation jump; Vv_{IMIT} = maximum achieved vertical velocity of the skier in imitation jump; VvB_{IMIT} = vertical velocity at the point of heel lift-off in imitation jump; $\dot{V}O_{2peak}$ = peak oxygen uptake from incremental test to exhaustion; DP = double poling; UB = upper-body; LM = lean-mass; GE = gross efficiency; CL = cycle length.

[a] Spearman's ρ correlation

*p<0.05

[#]p<0.01

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body lean-mass. The latter is of particular interest for the NC athlete, as the upper-body power capacity must be balanced with a low body-mass to optimize SJ performance.

In contrast to established performance characteristics among elite XC skiers [3, 4, 17], no correlation between neither submaximal gross efficiency nor cycle length with XC performance was found here. The large variation in body-mass-normalized $\dot{V}O_{2peak}$ found in the current study, ranging from 66.9 to 80.8 ml·kg^{-1}·min^{-1}, may result in gross efficiency being a less important performance measure for XC skiing among elite NC athletes compared to XC skiers with more homogenous $\dot{V}O_{2peak}$ levels. Also the lack of association between cycle length and XC performance may be related to the heterogeneous study group; for example in cycling, variation in muscle fiber type distribution has been found impact the energetically optimal cadence [31]. However, as we do not have muscle biopsy of these athletes, this is something future studies need to investigate.

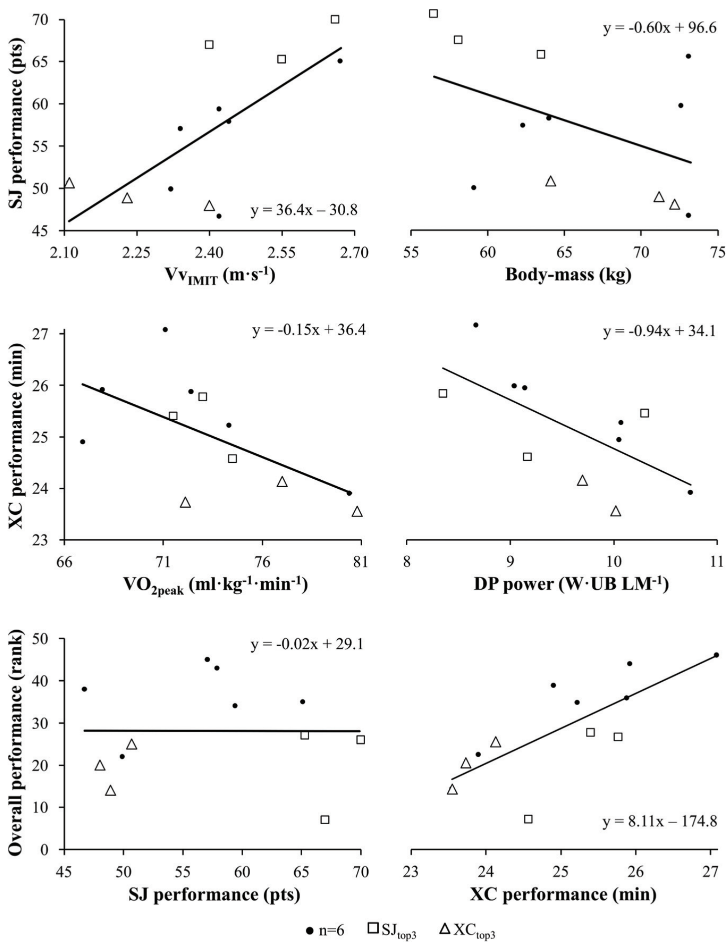

Fig 2. Ski jumping (SJ) and cross-country (XC) performance in relationship to the sport-specific capacities that combined best explained the variance in performance, as well as overall performance in relationship to the SJ and XC performance for the 12 international Nordic combined world-cup athletes. The data points represent the top 3 ranked ski jumpers (□ SJ_{top3}), top 3 ranked XC skiers (Δ XC_{top3}), and the remaining 6 athletes of the study (• n = 6). The lines were obtained by linear regression. Vv_{IMIT} = maximum achieved vertical velocity of the skier in imitation jump; $\dot{V}O_{2peak}$ = peak oxygen uptake from incremental test to exhaustion; DP = double poling; UB LM = upper-body lean-mass.

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Since the athletes' capacities were tested in a laboratory setting, some of the constraints are clearly different than the performance settings measured outdoors on snow. For example, the jump capacity for SJ is measured using full friction forces during push-off while the actual ski jump is executed while gliding in high speed on ice tracks with close to zero friction. Hence, the laboratory test enables the skier to employ a movement strategy that is not fully possible to perform at the take-off in the jumping hill [32]. In the XC roller ski test, the roller skis are shorter than skis and the wheels have different rolling friction and push-off mechanics. This may allow for slightly different technical strategies compared to on-snow skiing, which may especially have an impact on the gross efficiency measure. However, the scope of this study was indeed to elucidate the association of laboratory capacities in sport specific movement techniques used for monitoring athletes' development during the training year and field performance. Hence, in-depth technique comparisons of laboratory versus field SJ and XC skiing should be investigated in follow-up studies.

Of the sport-specific laboratory determinants investigated in this study, body-mass-normalized $\dot{V}O_{2peak}$ alone best predicted overall NC performance. This can largely be explained by the fact that in this specific event, XC performance had a significant correlation with overall NC performance while SJ performance did not. In addition, a high body-mass-normalized $\dot{V}O_{2peak}$ is influenced both by the absolute $\dot{V}O_{2peak}$ and body-mass, which separately were shown as important determinants for XC skiing and SJ performance, respectively. From a general perspective, it is rather unique that NC athletes with explosiveness close to the upper human limits are able to obtain $\dot{V}O_{2peak}$ values as high as 80 ml·kg^{-1}·min^{-1}. Whether the impact of SJ versus XC performance, and the associations to laboratory capacities, on the overall NC result apply to other venues and conditions (i.e. wind, snow, etc.) need to be investigated further. Although a definite conclusion cannot be made from this study, it constitutes an important point-of departure for future studies on the sport of NC.

Conclusion

Vertical IMIT velocity and body-mass in combination best predicted SJ performance, whereas body-mass normalized $\dot{V}O_{2peak}$ and upper-body power best predicted XC skiing performance. The test capacities provided for the best SJ and XC skiers among our 12 NC athletes may serve as reference values for world-class performance in these events. Specifically, the 3 best SJ obtained a group mean of ~2.5 m·s^{-1} vertical velocity in the imitation jump with a body-mass of <60 kg, with the respective values being 12–15% different among the 3 best XC skiers. Interestingly, there was only 5% difference in vertical velocity in the squat jump between the two performance groups, which indicates that performance in the sport-specific movement of an imitation jump distinguishes performance groups more than pure vertical jump capacity. The 3 best XC skiers showed a group mean of >76 ml·kg^{-1}·min^{-1} in $\dot{V}O_{2peak}$ and upper-body power of 344 W and 5.1 W·kg^{-1}, being respectively 5%, 21%, and 6% higher than the 3 best SJ.

Overall, the concurrent development of $\dot{V}O_{2peak}$, upper-body power, and SJ-specific vertical jump capacity while minimizing body-mass within the BMI limit set by FIS should be considered in the seasonal training of NC athletes.

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Author Contributions

Conceptualization: Vegard Rasdal, Ronny Fudel, Jan Kocbach, Frode Moen, Gertjan Ettema, Øyvind Sandbakk.

Data curation: Vegard Rasdal, Jan Kocbach, Gertjan Ettema.

Formal analysis: Vegard Rasdal, Ronny Fudel, Jan Kocbach, Gertjan Ettema, Øyvind Sandbakk.

Funding acquisition: Frode Moen, Gertjan Ettema, Øyvind Sandbakk.

Investigation: Vegard Rasdal, Ronny Fudel, Jan Kocbach, Frode Moen, Gertjan Ettema, Øyvind Sandbakk.

Methodology: Vegard Rasdal, Ronny Fudel, Jan Kocbach, Frode Moen, Gertjan Ettema, Øyvind Sandbakk.

Project administration: Vegard Rasdal, Ronny Fudel, Jan Kocbach, Øyvind Sandbakk.

Supervision: Gertjan Ettema, Øyvind Sandbakk.

Visualization: Vegard Rasdal, Ronny Fudel, Jan Kocbach, Øyvind Sandbakk.

Writing – original draft: Vegard Rasdal, Øyvind Sandbakk.

Writing – review & editing: Vegard Rasdal, Ronny Fudel, Jan Kocbach, Frode Moen, Gertjan Ettema, Øyvind Sandbakk.

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Study II

Study II

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Study III

Study III

Study IV

Study IV

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CASE REPORT
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The Long-Term Development of Training, Technical, and Physiological Characteristics of an Olympic Champion in Nordic Combined

Vegard Rasdal[1], Frode Moen[1,2] and Øyvind Sandbakk[1]*

[1] Centre for Elite Sports Research, Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology, Trondheim, Norway, [2] Department of Education, Norwegian University of Science and Technology, Trondheim, Norway

Nordic combined requires high technical skills and vertical impulse for the ski-jumping event and aerobic endurance, ski efficiency and finish-sprint abilities to succeed in the subsequent cross-country race. The main aim of this study was to investigate the development of training, technical, and physiological characteristics during the last four seasons preceding the Olympic Games in a Nordic Combined Champion [∼74 kg (63 kg lean-mass)]. During the first season of the 4-year cycle, the development of lower-body muscle-mass and vertical jump velocity was prioritized, after which the emphasis on developing the technical abilities were increased over the following three seasons. While maintaining his vertical velocity in countermovement jump at ∼3 m·s^{-1}, despite an increase of 7 kg overall body-mass, the participant improved his vertical velocity in sport-specific ski jump imitation with 0.31 m·s^{-1} coincidentally with high technical focus, including use of systematic mental training to enhance skill acquisition, and an almost twofold increase of annual imitation jumps in the four-season cycle. Endurance training increased from 462 h·season^{-1} in season one to 635 h·season^{-1} in season three, which was mainly due to more low-intensity training. Thereafter, endurance training in the Olympic season was reduced by 12% and more focus was placed on quality of each session and sufficient recovery. The highest $\dot{V}O_{2peak}$ (5.36 L·min^{-1} and 72.0 ml·kg^{-1}·min^{-1}) was measured in the third season and thereafter maintained, although competition results were further improved toward the Olympics. The amount of moderate- (31.9 ± 2.8 h·season^{-1}, 43.0 ± 3.9 sessions·season^{-1}) and high-intensity (28.3 ± 3.1 h·season^{-1}, 52.3 ± 2.7 sessions·season^{-1}) endurance training was stable throughout the four-season period, with >65% being performed as skiing or roller ski skating. Development of finish-sprint ability was an important strategy throughout the entire period, and both Olympic gold medals were won in a finish-sprint. Altogether, this study provides unique data from the four-season cycle of a two-time Olympic gold medal winner in Nordic Combined, where high amounts of strength/power and endurance training is successfully combined toward a peak in the Olympic season. This knowledge shows how the combination of long-term endurance and strength/power may be optimized, and generates new hypotheses to be tested in future research.

Keywords: endurance training, high-intensity training, mental training, strength training, power, periodization, tapering, concurrent training

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****Correspondence:***
Øyvind Sandbakk
oyvind.sandbakk@ntnu.no

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INTRODUCTION

Nordic Combined (NC) is a challenging Olympic winter sport where the athletes compete in both a ski-jumping event and a cross-country race on the same day (Rasdal et al., 2017). Ski-jumping requires well developed technical abilities, flexibility, high vertical impulse and low body-mass (Schwameder, 2008; Muller, 2009; Sandbakk et al., 2016; Rasdal et al., 2017), in addition to mental awareness and toughness to successfully solve the different phases of a ski jump (i.e., in-run, take-off, transition to flight, flight, preparation for landing, landing). However, the take-off is widely considered most important (Schwameder, 2008; Virmavirta et al., 2009), and a recent study showed vertical velocity achieved in ski jump imitation together with body-mass to account for 70% of the variance in SJ performance in a world cup NC event (Rasdal et al., 2017).

The athletes' performance in the SJ event results in a proportional time penalty for the following 10-km cross-country skiing pursuit race in the skating style (Rasdal et al., 2017). The ∼25-min cross-country race is performed in varied terrain, in which high aerobic capacity, skiing efficiency and finish-sprint ability is important for performance (Sandbakk et al., 2010; Sandbakk and Holmberg, 2014; Tønnessen et al., 2015; Rasdal et al., 2017).

While there are numerous athletic disciplines where a combination of both endurance and strength/power are required for successful performance, none are as extreme as NC. Hence, the simultaneous development of ski-jumping and cross-country capacity in NC athletes is challenging, and its extreme combination is under-explored. Although only ∼50–60% of the ski-jumping and cross-country specialists' training is executed by NC athletes in each discipline, they differ only 10–17% in the various laboratory capacities (Sandbakk et al., 2016). Finally, the athlete need to develop mental abilities to optimize both the highly complex technical task in ski-jumping and the physical demanding cross-country event.

The main aim of this study was to investigate the development of training, technical, and physiological characteristics of a NC athlete during a four-season cycle prior to winning two Olympic gold medals at the 2014 Sochi Winter Olympics.

MATERIALS AND METHODS

Participant

The participant (born in 1991) specialized in NC in 2007 and progressively improved performance over the four-season cycle preceding the 2014 Winter Olympics in Sochi where he won two gold medals in NC. See **Table 1** for laboratory capacities in this period that constitutes his four competitive seasons in the World Cup.

The study was approved by the Norwegian Social Science Data Services (NSD), and the participant provided written informed consent to participate in the study.

Laboratory Testing

General vertical jumps [i.e., countermovement (CMJ) and squat jumps (SQJ)] and sport specific imitation jumps (IMIT) were performed two to three times each season from 2011 to 2012 that was his first season on the national team. Test results from the general preparation phase (GP) was used for descriptive analysis. Equipment and procedures are previously described (Sandbakk et al., 2016; Tønnessen et al., 2016) and, in all jumps, maximum vertical velocity of the center of mass was used for further analysis.

Physiological testing on roller skis was done two to three times each season, and results from GP was used for descriptive analysis. Three or four 5-min submaximal stages to compare physiological response at 4 mmol·L^{-1} blood lactate concentration, and an incremental maximal roller ski test to determine $\dot{V}O_{2peak}$ were performed. Equipment and procedures are previously described (Sandbakk et al., 2010, 2016) and, in all cases, respiratory variables (including determination of $\dot{V}O_{2peak}$) were calculated according to a previous study (Sandbakk et al., 2016).

One month after the 2014 Winter Olympics, the participant also performed DXA-measurement, from which lean-body-mass is reported.

Training Monitoring and Systematization of Training Data

The participant recorded his day-to-day training in a digital diary[1] as previously described (Tønnessen et al., 2016), with all training sessions being systemized and analyzed in Microsoft Office Excel 2016 (Microsoft, Redmond, WA, United States). Endurance sessions were registered using the *modified session-goal approach* (Sylta et al., 2014) as low-intensity (LIT), moderate-intensity (MIT), and high-intensity (HIT) zones and further split into various types of session-categories within each zone, as previously described (Solli et al., 2017). In addition, an own class for recovery, warm-up, and cool-down was defined (WUP).

When speed training was integrated into endurance sessions, 2 min per sprint was registered as speed training. Non-endurance training, such as ski-jumping and strength/power sessions, were registered from the start to the finish of the specific part of the session, including recovery periods between sets. Dry land technique-training was reported as ski-jumping time, and is solely reported as the number of IMITs performed.

Training data are presented annually and divided into different periodization phases, based on key periodization models (Issurin, 2010; Tønnessen et al., 2016) that are slightly modified due to personal communication with the athlete and his coach; Phase 1 (GP1; June–August) and Phase 2 (GP2; September–October) of the General Preparatory Phase, Specific Preparatory Phase (SP; November–December), and Competition Phase (CP; January–March).

Furthermore, in-depth taper analysis of the 2013–2014 Olympic season, including weekly training data over the last 6 weeks and daily training content in the 14 days preceding

[1]www.olt-dagbok.net

TABLE 1 | Laboratory capacities determined during the ground preparation phase from 2010–2011 to 2013–2014, as well as immediately after the Olympic Games (Post) in an Olympic Nordic Combined Champion.

		2010–2011	2011–2012	2012–2013	2013–2014	Post
Body-mass	(kg)	66.5	73.2	74.5	73.8	75.3
Vertical jump velocity						
Vv_{SQJ}	($m \cdot s^{-1}$)		2.91	2.94	2.96	3.05
Vv_{CMJ}	($m \cdot s^{-1}$)		3.04	3.05	3.13	3.10
Vv_{IMIT}	($m \cdot s^{-1}$)		2.14	2.37	2.34	2.45
Maximal aerobic power						
$\dot{V}O_{2peak}$	($ml \cdot kg^{-1} \cdot min^{-1}$)	68.8	69.3	72.0	71.0	72.1
	($L \cdot min^{-1}$)	4.58	5.07	5.36	5.24	5.43
Responses at 4 mmol·L^{-1} BLa						
$\dot{V}O_2$	($L \cdot min^{-1}$)	3.51	4.01	4.36	4.21	4.31
	($ml \cdot kg^{-1} \cdot min^{-1}$)	52.8	54.8	58.3	57.0	57.3
	(% peak)	77	79	81	80	79

**The test with the highest performance level in the period June–October was selected for analysis in the seasons 2010–2011 to 2013–2014. To better reflect the performance level required for the Olympics, also tests immediately post 2013–2014 season was selected (post). Vv_{SQJ}, maximum achieved vertical velocity in squat jump; Vv_{CMJ}, maximum achieved vertical velocity in countermovement jump; Vv_{IMIT}, maximum achieved vertical velocity in imitation jump; $\dot{V}O_{2peak}$, peak oxygen uptake from incremental test to exhaustion; BLa, blood lactate concentration; $\dot{V}O_2$, oxygen uptake.*

winning Olympic gold medal, are presented. Of the 6 weeks, the final 2 weeks before winning the first gold medal was defined as peaking phase and the preceding 4 weeks as pre-peaking phase.

Qualitative Analyses

To track missing data, ensure compliance with the training diary commentaries, and to verify the intensity of different training sessions, two interviews with the participant were conducted during the data-analysis phase of this study. Also two interviews with the participant's main coach was conducted to gather a qualitative representation of determining factors for the participant's success. In order to gain an overall understanding of the development of ski-jumping, we performed multi-disciplinary workshops with the authors of this study, his ski-jumping-coach and the mental coach to analyze training logs, tests and competition results, as well as videos and focus during the mental training throughout these seasons.

RESULTS

The participant recorded 804, 824, 1,008, and 950 training hours·season^{-1} from 2010–2011 to 2013–2014, distributed across 472, 519, 582, and 585 training sessions. The detailed development of the various training components is depicted in **Figure 1**. The participant gained ∼7 kg of body-mass from 66.5 kg in 2010–2011 to 73.2 kg in 2011–2012, and thereafter stabilized at ∼74 kg (**Table 1**). Lean body-mass was measured shortly after the Olympics to be 63.0 kg.

Non-endurance

Whereas the amount of general strength/power training varied as a sine wave between 90 and 140 h·season^{-1}, the amount of ski-jump specific strength/power training and the number of IMITs increased steadily each season (**Figures 1A,B**). Coincidentally, the vertical jump velocity in SQJ and CMJ varied less than 5%, whereas the vertical velocity in IMIT showed a 14.5% increase from 2.14 to 2.45 m·s^{-1} in the same period (**Table 2**). The participant reported that the compilation of strength/power sessions in 2010–2011 season was focused toward building lower-body muscle-mass and maximal strength, whereas more high-velocity exercises in ski-jump-specific movement patterns were emphasized from 2011 to 2012. High focus was put on improving ankle-flexibility and hip/core control in the ski-jump-specific movement, and at the same time technically aim to (1) reduce fluctuations of the center of mass in relation to the center of pressure in the in-run and (2) have the center of mass placed vertically above the center of pressure (i.e., lower lever-arm) during the take-off phase.

Endurance

The participant increased his aerobic capacity by 0.78 L·min^{-1} from 2010–2011 to 2012–2013 season, whereas his body-mass-normalized $\dot{V}O_{2peak}$ was relatively stable across the entire period (**Table 2**). $\dot{V}O_2$ at 4 mmol·L^{-1} blood lactate concentration increased from 77% in 2010–2011 to >80% of $\dot{V}O_{2peak}$ (**Table 2**).

The participant had a polarized periodization in all seasons, with the overall variation in endurance training volume mainly manipulated by LIT (**Figure 1C**). The amount of MIT and HIT was almost identical in all four seasons, except from a 22% decrease in the amount of MIT from 2012–2013 to 2013–2014 (**Figure 1C**). The main type of intervals for MIT and HIT sessions were in the range of 6–15 min and 3–5 min, respectively (**Table 2**). For all intensities, the average session duration was shorter in SP and CP compared to GP1 and GP2 (**Table 2**). The participant included sprints in nearly all LIT sessions on roller skis and skis, while sprints at the end of some of the MIT/HIT sessions stressed the ability to maintain a well-executed technique when fatigued. Sprint training was included 101, 114, 126, and 129 times·season^{-1} in the respective seasons from 2010–2011 to 2013–2014, and was usually performed as approximately ∼5 sprints of 6–8 s.

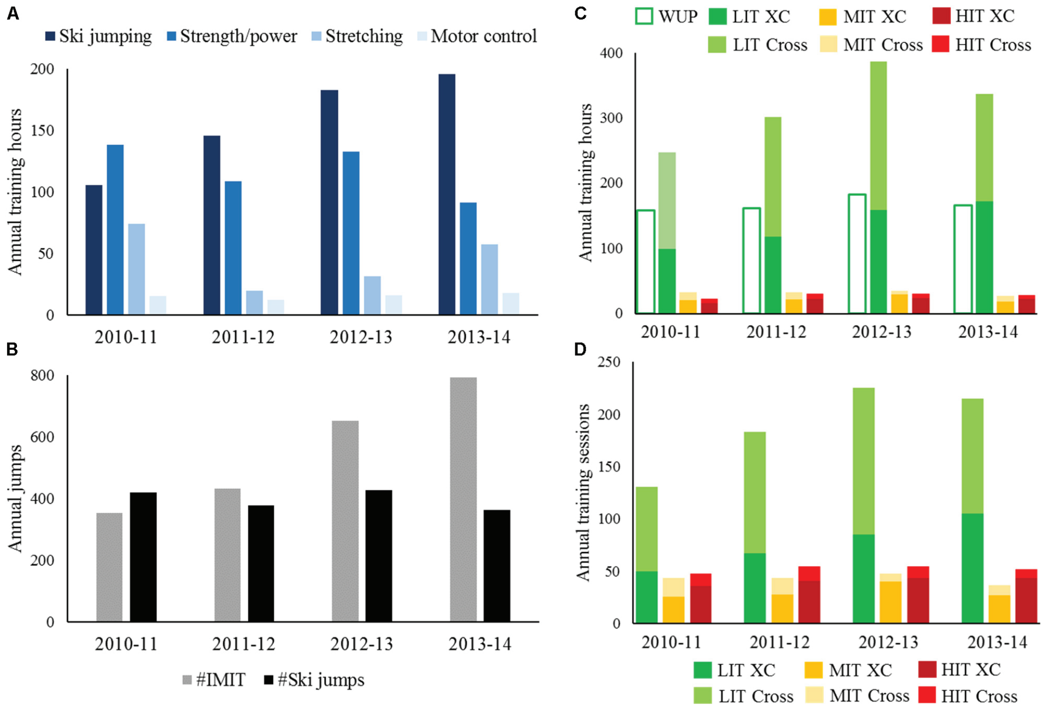

FIGURE 1 | Annual non-endurance training hours **(A)** and number of jumps **(B)**, as well as annual endurance training hours **(C)** and sessions **(D)** from the seasons 2010–2011 to 2013–2014 in an Olympic Champion in Nordic Combined. IMIT, dry-land imitation jump of a ski jump; WUP, time spent for warm-up, cool-down, and recovery; LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training; XC, cross-country session employing skating technique; cross, endurance session not employing cross-country skating technique.

The amount of endurance training was distributed equally between specific and unspecific training modes (i.e., 45, 44, 47, and 54% cross-country skating in the respective seasons from 2010–2011 to 2013–2014). More than two-thirds of MIT and HIT was performed on skis or roller-skis in all seasons, whereas for LIT 50–60% cross training was performed (**Figures 1C,D**).

Although some training camps throughout the cycle was at altitude > 1,500 m above sea level, no systematic altitude training was performed.

Tapering

The weekly distribution of training during the final 6 weeks and daily description of the final 2 weeks prior to winning the first gold medal is presented in **Tables 3A,B**. Overall, the training load and distribution between endurance and non-endurance training was similar for all six preceding weeks, except from week −4 and −2 (**Table 3A**), in which total training volume was ∼25% lower in both weeks compared to the other four. The reduction of training load in week −2 was mainly a result of traveling, whereas the reduction in week −4 was a consequence of no ski jumping. The weekly amount of endurance training in week −4 was two-thirds higher compared to the other 5 weeks. From pre-peaking phase to peaking phase, the overall training volume was reduced by 8% whereas endurance training volume was reduced by 25%.

Qualitative Assessment

The participant was involved in multiple of sport disciplines until the start of high-school, when he decided to specialize in NC at the age of 16. Since then, he had a close and well-functioning working-alliance with the same, high-level coach, with all training directed toward sport-specific goals. He was also part of a well-functioning training group that included two of the world's best NC athletes throughout the entire period. Here, regular team processes and daily training provided the possibility to develop and train at the highest level. During this period, he used mental training systematically to improve ski-jump-technique by, e.g., developing an automatized awareness of in-run position and balance and to optimize the take-off dynamics, especially in stressful situations in the hill. Although the participant quickly improved technical skills in dry-land training, the ability to translate this to the ski-jumping hill was more gradual. Hence, his ability to perform on top in important competitions were gradually improved and optimized toward the Olympics.

TABLE 2 | Mean session duration and number of monthly training sessions of the different endurance session categories in each intensity zone across seasons and periodization phases from 2010–2011 to 2013–2014 in an Olympic Nordic Combined champion.

	Per season				Mean ± SD of the four-season cycle				2013–2014			
	2010–2011	2011–2012	2012–2013	2013–2014	GP1	GP2	SP	CP	GP1	GP2	SP	CP
Mean session duration												
LIT (hrs·sess^{-1})	1.9	1.6	1.7	1.6	1.7 ± 0.2	1.7 ± 0.1	1.6 ± 0.1	1.5 ± 0.1	1.6	1.6	1.4	1.3
MIT (min·sess^{-1})	44.1	45.2	44.2	44.5	51.2 ± 2.3	48.1 ± 6.1	43.4 ± 4.3	32.2 ± 2.3	53.1	54.6	38.5	29.6
HIT (min·sess^{-1})	28.9	34.2	33.5	32.8	35.7 ± 3.5	41.3 ± 3.9	29.8 ± 3.6	27.7 ± 1.0	36.9	39.5	33.4	27.8
Categories LIT												
<50 min (sess·mth^{-1})	0.2	2.3	2.2	1.5	1.6 ± 1.2	1.5 ± 0.9	2.0 ± 1.3	1.8 ± 0.8	1.0	1.5	2.5	1.7
50–90 min (sess·mth^{-1})	1.8	3.6	4.1	6.1	4.2 ± 1.7	2.6 ± 1.2	3.7 ± 1.9	5.3 ± 2.3	6.5	3.4	6.9	7.7
90–120 min (sess·mth^{-1})	4.9	3.0	5.3	5.2	6.4 ± 2.4	5.7 ± 1.1	5.0 ± 1.2	2.3 ± 1.4	9.5	6.9	3.4	2.0
>120 min (sess·mth^{-1})	3.8	6.2	6.8	4.9	5.0 ± 1.3	6.5 ± 2.9	5.3 ± 0.9	3.7 ± 1.1	3.6	5.4	5.9	3.3
Categories MIT												
Continuous (sess·mth^{-1})	0.1	0.2	0.1	0.3	0.2 ± 0.2	0.2 ± 0.2	0.1 ± 0.2	0.0 ± 0.0	0.3	0.5	0.5	0.0
<8 min (sess·mth^{-1})	1.1	1.1	1.5	0.7	0.7 ± 0.3	1.0 ± 0.6	1.6 ± 0.4	1.7 ± 0.6	0.7	0.5	1.5	1.0
8–15 min (sess·mth^{-1})	1.1	0.7	1.5	1.1	1.6 ± 0.3	1.4 ± 0.2	0.9 ± 0.4	0.8 ± 0.4	2.0	1.0	1.0	0.7
>15 min (sess·mth^{-1})	0.0	0.3	0.0	0.1	0.2 ± 0.3	0.1 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	0.0	0.5	0.0	0.0
Unspecified (sess·mth^{-1})	1.4	1.2	0.9	0.8	2.0 ± 0.8	1.2 ± 0.5	0.5 ± 0.6	0.7 ± 0.6	1.0	1.0	0.0	0.7
Categories HIT												
Continuous (sess·mth^{-1})	0.3	2.5	2.5	2.4	1.5 ± 0.4	1.4 ± 0.4	3.1 ± 0.7	5.2 ± 0.2	2.0	1.5	2.0	5.0
<3 min (sess·mth^{-1})	0.0	0.0	0.1	0.0	0.0 ± 0.0	0.1 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0
3–5 min (sess·mth^{-1})	0.5	1.1	1.2	1.2	0.7 ± 0.6	1.4 ± 0.7	1.0 ± 0.6	1.2 ± 0.2	0.7	2.5	1.0	1.0
>5 min (sess·mth^{-1})	0.1	0.3	0.2	0.3	0.2 ± 0.4	1.0 ± 0.8	0.1 ± 0.2	0.0 ± 0.0	0.0	1.5	0.5	0.0
Unspecified (sess·mth^{-1})	0.4	0.5	0.6	0.3	1.1 ± 0.4	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.1	1.0	0.0	0.0	0.3

GP, general preparatory phase; SP, specific preparatory phase; CP, competition phase; LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training.

TABLE 3 | Weekly training content during the final 6 weeks **(A)** prior to winning two individual gold medals in the 2014 Sochi Winter Olympics, with detailed description of the training performed during the last 14 days **(B)** in an Olympic Nordic Combined champion.

A	**Weekly training content during the final 6 weeks prior to gold medal**					
Week	**Non-endurance hours (sessions)**	***SJ hours (sessions)***	**Endurance hours (sessions)**	***XC MIT hours (sessions)***	***XC HIT hours (sessions)***	**Total hours (sessions)**
−6	10.3 (6)	*7.3 (5)*	8.7 (6)	*0.0 (0)*	*0.8 (2)*	18.9 (12) Two competitions
−5	10.6 (6)	*8.2 (5)*	10.2 (7)	*0.0 (0)*	*1.5 (3)*	20.8 (13) Three competitions
−4	1.8 (3)	*0.0 (0)*	14.8 (8)	*0.8 (1)*	*0.0 (0)*	16.7 (11)
−3	11.4 (9)	*6.3 (5)*	8.9 (5)	*0.0 (0)*	*1.2 (2)*	20.4 (14)
−2	7.1 (4)	*3.9 (3)*	7.9 (5)	*0.0 (0)*	*0.8 (2)*	15.0 (9)
−1	11.5 (5)	*6.7 (4)*	9.1 (7)	*0.7 (2)*	*0.0 (0)*	20.6 (12)
0	*Individual gold medal, Olympic Winter Games 2014*					

B	**Daily training content during the last 2 weeks prior to gold medal**	
Day	**AM**	**PM**
−14	*Rest day*	
−13	1.5 h strength/power*	1.5 h LIT with 4 × 6–8 s sprints, XC
−12	0.75 h LIT, running + 0.25 h flexibility	*Travel*
−11	*Travel day*	
−10	1.5 h LIT, running	1 h dry land technique session
−9	2 h SJ[c]*	5 × 3 min HIT[d], XC
−8	2 h SJ[c]*	1 h LIT, XC
−7	2 h SJ[c]*	1 h LIT, XC
−6	1.5 h strength/power*	0.3 h LIT, running + 0.3 h flexibility
−5	0.5 h LIT, running	1.25 h LIT, running
−4	0.3 h LIT, running + 0.7 h flexibility	0.25 h flexibility
−3	2.5 h SJ[c]*	5 × 7 min MIT[d], XC
−2	2.5 h SJ[c]*	1.25 h LIT, XC
−1	2 h SJ[c]*	1 h LIT with 3 × 8 s sprints, XC
0	*Individual gold medal, Olympic Winter Games 2014*	

*[c]Official ski jumping training in relation to competition. [d]MIT and HIT sessions normally included 20–40 min of LIT as warm-up and 15–30 min LIT as cool-down. SJ, ski jumping session; XC, cross-country skiing employing skating technique; technique session, exercises designed to imitate ski jumping on dry land; LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training. *Time of non-endurance sessions is from start to the end of session, including warm-up and recovery between sets.*

Sequencing of sessions throughout the seasons was based on the competition format of the sport, i.e., with strength/power and ski-jump sessions performed early in the day and endurance sessions in the afternoon with 2–4 h in between (when performed on the same day). For seasonal periodization, the GP1 contained relatively more focus on strength/power and high load of endurance training, whereas the focus on key development sessions (i.e., SJ sessions, and intervals on roller skis/skis) increased from GP2 toward CP.

DISCUSSION

The present study investigated the development of training, technical, and physiological characteristics during the last four seasons preceding the Olympic Winter Games in an Olympic NC Champion. After an initial focus of increasing lower-body muscle-mass and vertical jump velocity, the participant had a greater emphasis on technical sessions over the following three seasons. At the same time, the athlete was included in a group of world-class NC athletes and systematic mental training to enhance skill acquisition was included. After a progressive increase of endurance training over the first three seasons, this was reduced by 12% in the Olympic season. While maintaining his CMJ vertical jump velocity at ∼3 $m \cdot s^{-1}$, despite an increase of 7 kg overall body-mass, the participant improved his vertical jump velocity of sport-specific IMITs with 0.31 $m \cdot s^{-1}$ and $\dot{V}O_{2peak}$ with ∼0.8 $L \cdot min^{-1}$ coincidentally with an almost twofold increase of annual IMITs and an increase of ∼200 annual endurance hours in the four-season cycle. An emphasis on improving finish-sprint ability in cross-country skiing was present in all seasons, a determining factor since both Olympic gold medals were won in the finish-sprint. Tapering toward the Olympic included a 25% reduction in endurance training volume and an 8% increase in non-endurance training from pre-peaking to peaking phase.

Non-endurance

Already in 2011, the athlete had reached a world-class vertical jump velocity of ~2.9 $m \cdot s^{-1}$ in CMJ and SQJ (Tønnessen et al., 2016; Rasdal et al., 2017). This was likely a consequence of the strength/power focus in the 2010–2011-season, compiled toward muscle hypertrophy and maximal lower-body strength. Thereafter, strength/power sessions were focused more toward high-velocity exercises with ski-jump-specific movement pattern. This shift of exercise content, with more specificity when the level of strength was sufficient, also allowed for maintaining his jump capacity along with the large increase of endurance training that often induce negative influence on power development (Nader, 2006; Wilson et al., 2012; Baar, 2014). Coinciding the increase in the number of IMITs, ski-jump-specific vertical jump velocity improved with ~15%, indicating that the execution of this technical skill was not negatively influenced by concurrent endurance training. Overall, it may be beneficial for NC athletes to improve strength and vertical impulse at an early phase, followed by a greater focus on high-velocity exercises in a ski-jump-specific movement pattern when increasing the annual endurance load.

With an in-run speed of 85–95 $km \cdot h^{-1}$ and less than 0.35 s to complete the take-off (Muller, 2009), the athlete relies on an automated and technically optimized take-off pattern. Improved ankle-flexibility and hip/core control enabled our participant to solve the task (see description in the "Results" section) well during dry-land training and testing already early in the Olympic cycle, but it required longer time to transfer this skill to ski-jumping in the hill. Here, systematic mental training to enhance skill acquisition supported the technique training, which was likely a crucial factor for the participant's success at the Olympic Games. Since we do not have good quantitative measurement of these aspects of the ski-jump technique, future studies should strive to develop and validate such measurements both for laboratory and field testing.

Endurance

The polarized intensity model and overall endurance volume of ~560 $h \cdot season^{-1}$ in the Olympic season is similar to earlier reported values from successful seasons in NC athletes (Tønnessen et al., 2016). The amount of endurance training was, however, increased by an average of 87 $h \cdot season^{-1}$ over the initial three seasons, having a peak of 635 $h \cdot season^{-1}$, followed by a reduction in the Olympic season. While this is clearly lower than top-level cross-country skiers who progress their training up to ~8–900 annual endurance training hours (Sandbakk and Holmberg, 2014; Solli et al., 2017), NC athletes train more hours than cross-country skier when including their ski-jumping training (Sandbakk et al., 2016). However, the annual training cannot be directly compared between the two winter sports as the different loads of cross-country versus ski-jumping training and the subsequent risk of overreaching must be considered differently. Nevertheless, the current study indicates that a progressive increase in endurance training load during an Olympic cycle followed by a reduction in the peak season may be beneficial for overall long-term development in NC.

The annual increase in endurance training load until the 2012–2013 season, coupled with 7 kg increase in body-mass, led to a gradual increase of $\dot{V}O_{2peak}$ up to 5.36 $L \cdot min^{-1}$ and 72.0 $ml \cdot kg^{-1} \cdot min^{-1}$, which is within previously reported benchmark values in world-class NC athletes (Tønnessen et al., 2015; Sandbakk et al., 2016; Rasdal et al., 2017). In the 2012–2013 season, ~80% of MIT and HIT sessions (compared to 70% before) was performed in skating, which most likely contributed to the increased utilization of $\dot{V}O_{2peak}$ at 4 $mmol \cdot L^{-1}$ of blood lactate, as well as a further increase in roller ski $\dot{V}O_{2peak}$ that season. The subsequent reduction of endurance training load from 2012–2013 to 2013–2014 was partly compensated by more skating also in the LIT zone, and might have led to maintenance of endurance capacity in the Olympic season. However, the lower endurance load may have reduced overall fatigue and thus improved the quality in the non-endurance sessions as well, enabling a further development of the vertical jump velocity in the Olympic season (measured after the 2013–2014 season). This may overall suggest that the reduction was beneficial for development of ski-jumping performance, and thus, the overall NC performance.

Tapering

The tapering strategy of 25% reduction in endurance training load from the pre-peaking phase to the peaking phase is somewhat higher than previously found in successful cross-country skiers and biathletes (Tønnessen et al., 2014; Solli et al., 2017), and is more than the 20% reduction recommended for achieving a tapering effect (Bosquet et al., 2007). Overall training load, however, was decreased by only 8% as non-endurance load was increased from pre-peaking to the peaking phase. Tønnessen et al. (2014) speculated in their study that the lower reduction in training volume found among elite cross-country skiers compared to what is suggested by the literature could be ideal in sports with a dense competition schedule. However, NC athletes are also dependent on ski-jumping facilities to be able to jump, and thus logistics govern much of their training plan. This may also explain the three-phase tapering format in the participants' endurance training load, where a 45% increase from week −5 to −4 was coupled with no ski-jumping in week −4. How to taper for an optimal ski-jumping performance has not previously been researched, and its delicate interplay with endurance training to achieve optimal NC performance sorely needs to be further investigated in future group studies.

CONCLUSION

Our study provides unique data from the four-season cycle of a two-time Olympic gold medal winner in NC. The participant focused on increasing lower-body muscle strength and vertical jump impulse early in the cycle, followed by increased emphasis on technical ski-jumping sessions and inclusion in a high-level training group. Here, improved ankle-flexibility and hip/core control, together with systematic mental training, gradually enabled our participant to solve the technical task in the hill. A progressive increase of low-intensity endurance training over the three first seasons was followed by reduced endurance training volume, but with a higher degree of specific training in the Olympic season to enable greater quality in each session and to trigger surplus in developing ski-jumping performance. Improving finish-sprint ability was emphasized in all seasons, and was a determining factor for winning both Olympic gold medals. Peaking toward the Olympics included an overload of endurance training in the pre-peaking phase before a 25% reduction in the peaking phase. Consequently, non-endurance training was increased from pre-peaking to the peaking phase and the overall training was not reduced more than 8%. Altogether, this study provides insight into how the combination of long-term endurance and strength/power training may be optimized, and generates new hypotheses to be tested in future group studies. In particular, detailed description and analysis of non-endurance training is lacking in the majority of studies on concurrent and strength/power sports. We thus encourage future studies to investigate the training load of strength/power, both as an isolated stimuli, and concurrently to endurance training.

AUTHOR CONTRIBUTIONS

VR, FM, and ØS designed the study, contributed to interpretation of the results, and contributed to the final manuscript. VR performed the data collection. VR and ØS performed the data and statistical-analysis and wrote the draft manuscript.

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