Ove Hukset Sollie // Determinants of performance in male and female adolescent competitive cross-country skiers

DISSERTATION FROM THE
NORWEGIAN SCHOOL OF
SPORT SCIENCES
2022

Ove Hukset Sollie

Determinants of performance in male and female adolescent competitive cross-country skiers

NIH NORWEGIAN SCHOOL
OF SPORT SCIENCES

nih.no

Ove Hukset Sollie

Determinants of performance in male and female adolescent competitive cross-country skiers

DISSERTATION FROM THE NORWEGIAN SCHOOL OF SPORT SCIENCES • 2022

ISBN 978-82-502-0601-4

Acknowledgements

The present work was carried out at the Norwegian School of Sport Sciences, Department of Physical Performance.

I would especially like to thank my supervisor, Professor Thomas Losnegard. Your great knowledge in the field of cross-country skiing, combined with your ability to provide good ideas and ask the right questions while still providing support and autonomy, has been of tremendous help. I am deeply thankful for all your efforts, patience and guidance throughout this work.

I would also like to thank the participants in this project. It was great working with both young upcoming athletes and world-class skiers in the same project. I wish the young skiers all the best in the future and it’s good to see that some of you are already performing at a high level.

Professor Jørgen Jensen, my supervisor during my master’s thesis, needs special thanks. Your inclusion of me in academia as a student and later as a research assistant impressed me and showed me how I want to include others. I also appreciate our cooperation on our “protein papers”.

Thanks to all my co-workers who helped with this project: Øyvind Gløersen for helping me with kinematics and various calculations; Bjarne Rud for helping with the treadmill during the testing periods; Professor Yngvar Ommundsen for helping with the questionnaires; and Magne Lund Hansen for helping with data collection. I would also like to thank the former head of the department, Professor Jostein Hallén. You suggested that I should apply for this PhD and also helped when I had questions regarding physiology or young athletes.

Thanks to master’s students Christian Steinbo and Kristian Holmsen for all your long hours in the lab during the data collection. I appreciate your hard work.

My final and biggest thanks go to my wife Randi for your support and patience. During this PhD we have moved, had a second child with a lot of sleepless nights, and combined home office and kindergarten through a pandemic. I am really looking forward to spending more time with you and the kids.

Oslo, November 2021

Table of contents

1 Summary

The process of adolescent cross-country (XC) skiers' development to become elite senior XC skiers is multifaceted, and a complementary mix of athletic attributes has to be acquired and improved. This includes physiological attributes such as a high energy turnover and efficient movement economy; applying tactics in racing situations; and the ability to learn training methods, tactics and technique. Given the complex and demanding nature of XC skiing and the lack of research in adolescent XC skiers, a broad approach to explore the determinants of performance in male and female adolescent skiers is warranted. Such information may provide important insights for the development of performance in XC skiers.

This research project used laboratory tests (**papers I-II**) and a combination of laboratory tests with novel in-field experimental approaches (**papers III-IV**) to explore the determinants of XC skiing performance in male and female adolescent competitive XC skiers.

In **papers I-II**, we explored the physiological determinants of performance in male and female adolescent skiers (**paper I**) and sex differences in these determinants within adolescent (~15 yrs), junior (~18 yrs) and senior (~28 yrs) XC skiers (**paper II**). Gross efficiency (GE), peak oxygen consumption ($\dot{V}O_{2peak}$) and accumulated oxygen deficit (ΣO_{2def}) were calculated from treadmill roller ski skating. Upper- and lower-body maximal strength were also tested. On-snow performance (distance and sprint) for the adolescents in paper I was established from unofficial national championship results for this age group.

The sex differences in XC skiing performance ranged from ~15–25% in the lab-based performance tests and were similar between the different age groups. The different physiological determinants affected performance similarly in adolescent boys and girls. $\dot{V}O_{2peak}$ seemed to be the most important physiological determinant in explaining sex differences in performance within all age groups, and the most important determinant for both laboratory and on-snow distance skiing in adolescent skiers. However, upper-body strength and body mass index seemed most important for on-snow sprint performance. Moreover, the complexity of on-snow skiing performance in adolescent skiers is highlighted, as $\dot{V}O_{2peak}$, ΣO_{2def} and GE explained ~80% of the variation in laboratory performance, but were substantially lower in explaining outdoor performance (~20-30% of the variation).

In **paper III**, we used a novel approach by combining laboratory measures with inertial measurement unit (IMU) and global navigation satellite system (GNSS) measures to describe pacing patterns and sub-technique selection during racing and compared these patterns to those of elite senior skiers. The skiers performed a free technique rollerski time trial (TT) over age-related racing distances using the GNSS/IMU system to track position and speed, and classify sub-techniques. Lab-based skiing economy and $\dot{V}O_{2peak}$ were used to calculate the relative oxygen demand ($\dot{V}O_{2dem}$) in 13 undulating and uphill segments of the race.

The adolescent skiers tended to exhibit higher mean exercise intensity than older and more experienced skiers (120 vs. 112% of $\dot{V}O_{2peak}$), with a more pronounced positive pacing pattern (130 vs. 110% of $\dot{V}O_{2peak}$ for the initial part of the race). Furthermore, the adolescents used more of the “low-speed sub-technique” Gear 2 (23 vs. 14%), less of the “high speed sub-technique” Gear 3 (36 vs. 45%) and had more frequent transitions between sub-techniques (~18 vs. ~15 transitions$\cdot$km^{-1}) than the elite seniors. Hence, differences in physical ability affect speed and sub-technique selections, implying a need for differentiating technical training for different ages and levels.

Technical training for adolescent athletes most often happens in large groups with a high athlete-to-coach ratio, which restricts coaches’ opportunities to provide individual feedback. Thus, organizing practice sessions to facilitate more individual feedback could be an important aspect of technique training. Therefore, in **paper IV**, we investigated the effects of observational feedback in an applied setting using a novel approach with a long-duration learning intervention. The adolescent skiers were divided into a control group and three intervention groups (dyad practice, video or coaching feedback), which practiced the Gear 2 sub-technique 6x30 min in total over a 5-week period, on rollerskis outdoors. High-speed performance and skiing economy were assessed on a rollerski treadmill before and after the intervention.

The video and coaching feedback groups improved high-speed performance during the intervention (2.1% and 3.8%, video and coaching respectively) and coaching feedback improved performance more than dyad practice. Overall, our data suggest that feedback from a competent coach is better than observation for improving performance in adolescent athletes. However, self-observation through video with attentional cues is seen as a promising tool for increasing valuable individual feedback when coaching large groups.

Overall, this thesis shows that the physiological determinants of XC ski performance and the sex difference in these determinants are similar in adolescent skiers (14-15 yrs) and older skiers. Further, adolescent skiers seem to use these physiological determinants in a similar manner to seniors in a racing situation, although with a more pronounced positive pattern and more use of “slow-speed sub-techniques”. Finally, we show that a competent coach is important for technique learning, but self-observation through video is a promising tool.

Sammendrag (summary in Norwegian)

Utvikling av unge langrennsløpere er komplisert, og en rekke komplementære egenskaper skal læres og utvikles. Dette innebærer utvikling av en høy energiomsetning og effektiv arbeidsøkonomi; utvikling av taktiske vurderinger i konkurranser; og evnen til å lære treningsmetodikk, taktikk og teknikk. Ettersom langrenn er en kompleks og krevende idrett, samt at lite forskning finnes på unge langrennsløpere, trengs det en bred tilnærming for å utforske viktige variabler for langrennsprestasjon for unge gutter og jenter. Dette kan gi bedre innsikt i hvordan best utvikle unge langrennsløpere.

Dette forskningsprosjektet benyttet laboratorietester (**artikler I-II**) og en kombinasjon av laboratorietester og avanserte feltmetoder (**artikler III-IV**) for å utforske viktige variabler for langrennsprestasjon hos unge konkurrerende gutter og jenter.

I **artiklene I-II** undersøkte vi hvordan ulike antropometriske og fysiologiske variabler påvirket langrennsprestasjon hos unge gutter og jenter (**artikkel I**) og hvordan kjønnsforskjellen var for disse variablene for ungdom (~15 år), juniorløpere (~18 år) og seniorløpere (~28 år) innen langrenn (**artikkel II**). Arbeidsøkonomi, maksimalt oksygenopptak ($\dot{V}O_{2peak}$) og akkumulert oksygenunderskudd (ΣO_{2def}) ble beregnet fra rulleskitester på tredemølle. Maksimal styrke for over- og underkropp ble også testet. Langrennsprestasjonen på snø (distanse og sprint) ble hentet fra det uoffisielle norgesmesterskapet (Hovedlandsrennet) for ungdommen i **artikkel I**.

Kjønnsforskjellene i langrennsprestasjonen på tredemøllen varierte mellom ~15–25% og var like mellom de forskjellige aldersgruppene. De ulike fysiologiske variablene påvirket også prestasjonen likt hos guttene og jentene. $\dot{V}O_{2peak}$ så ut til å være den viktigste fysiologiske variabelen til å forklare kjønnsforskjellen i prestasjon i alle aldersgrupper, og var den viktigste variabelen for både tredemølle- og distanseprestasjon på snø hos de unge langrennsløperne. Overkroppsstyrke og kroppsmasseindeks så imidlertid ut til å være de viktigste variablene for sprintprestasjon på snø. Dette forskningsprosjektet fremhever også kompleksiteten i langrennsprestasjon på snø, ettersom $\dot{V}O_{2peak}$, ΣO_{2def} og arbeidsøkonomi forklarte ~80% av variasjonen i tredemølleprestasjonen, mens disse variablene kun forklarte ~20–30% av variasjonen til langrennsprestasjonen på snø.

I **artikkel III** brukte vi en ny type tilnærming ved å kombinere tester innendørs på tredemølle med «inertial measurement units» (IMUs) og globale navigasjonssatellittsystemer (GNSS) utendørs for å beskrive pacingen og valg av delteknikker under konkurranse, og sammenlignet dette med seniorløpere. Langrennsløperne gjennomførte et testrenn i skøyting på rulleski over aldersrelaterte distanser hvor de brukte GNSS/IMU-systemet til posisjons- og hastighetsmålinger, og å klassifisere delteknikker underveis i testrennet. Arbeidsøkonomi og $\dot{V}O_{2peak}$ fra tredemøllen ble brukt til å beregne det relative oksygenkravet ($\dot{V}O_{2dem}$) i 13 ulike segmenter av løypa.

De unge langrennsløperne hadde en tendens til høyere gjennomsnittlig intensitet enn seniorløperne under rennet (120 vs. 112 % av $\dot{V}O_{2peak}$), med en mer positiv pacing (starte hardere, 130 vs. 110 % av $\dot{V}O_{2peak}$ i første del av løypa). De unge brukte også mer av "lavhastighetsteknikken" padling (G2, 23 vs. 14 %), mindre av "høyhastighetsteknikken" dobbeldans (G3, 36 vs. 45 %) og hadde hyppigere overganger mellom delteknikkene (~18 vs. ~15 overganger$\cdot$km^{-1}) enn seniorløperne. Fysiske forskjeller påvirker hastigheten, og dermed valg av delteknikker, noe som innebærer et behov for å differensiere teknisk trening for ulike aldersgrupper og nivåer.

Teknikktrening for unge utøvere skjer oftest i store grupper med mange utøvere per trener, noe som begrenser trenernes muligheter til å gi individuell tilbakemelding. Derfor kan organiseringen av treningsøkter for å legge til rette for mer individuell tilbakemelding være et viktig aspekt ved teknikktrening. Derfor undersøkte vi i **artikkel IV** effekten av observasjon på trening gjennom en intervensjonsperiode. Langrennsløperne ble delt inn i en kontrollgruppe og tre intervensjonsgrupper (pararbeid, se seg selv på video eller tilbakemelding fra trener), som trente padling 6x30 min totalt på rulleski utendørs over en 5-ukers periode. Sprintprestasjon og arbeidsøkonomi ble testet på en rulleskitredemølle før og etter intervensjonen.

Video- og trenergruppen forbedret sprintprestasjon gjennom intervensjonen (henholdsvis 2,1 % i video- og 3,8 % i trenergruppen) og tilbakemeldinger fra trener forbedret prestasjonen mer enn pararbeid. Samlet sett tyder resultatene på at tilbakemeldinger fra en kompetent trener er bedre enn observasjon for å forbedre prestasjon hos unge langrennsløpere. Selvobservasjon på video med stikkordsliste for hva som er god teknikk, kan fungere som et godt alternativt verktøy for å øke mengden individuell tilbakemelding i store utøvergrupper.

Dette forskningsprosjektet viser at de viktigste fysiologiske variablene for langrennsprestasjon og kjønnsforskjellen i disse variablene er like hos unge skiløpere (14-15 år) og eldre skiløpere. Videre ser det ut til at unge skiløpere bruker disse fysiologiske variablene på samme måte som seniorer i konkurranse, men med mer positiv pacing og mer bruk av "lavhastighetsteknikker". Til slutt viser vi at en kompetent trener er viktig for teknikklæring, men selvobservasjon på video er et lovende verktøy for teknikktrening.

List of papers

This dissertation is based on the following research papers, which are referred to in the text by their Roman numerals:

I. **Sollie O** & Losnegard, T. Anthropometrical and physiological determinants of laboratory and on-snow performance in competitive adolescent cross-country skiers. Submitted to *Frontiers in Physiology*.

II. **Sollie, O** & Losnegard, T. Sex differences in physiological determinants of performance within elite adolescent, junior and senior cross-country skiers. *International Journal of Sport Physiology and Performance.* Manuscript in revision.

III. **Sollie, O**, Gløersen, Ø, Gilgien, M, Losnegard, T. Differences in pacing pattern and sub-technique selection between young and adult competitive cross-country skiers. *Scandinavian Journal of Medicine and Science in Sport*. 2021; 31: 553– 563. https://doi.org/10.1111/sms.13887

IV. **Sollie, O**, Holmsen, K, Steinbo, C, Ommundsen, Y, Losnegard, T. Observational vs coaching feedback on non-dominant whole-body motor skill performance—application to technique training. *Scandinavian Journal of Medicine and Science in Sport*. 2021; 00: 1– 12. https://doi.org/10.1111/sms.14030

Abbreviations and explanations

1.1 Abbreviations

BM	Body mass
BMI	Body mass index
C	Cost of transportation
C_{rr}	Coefficient of rolling resistance
FFM	Fat-free mass
FIS	International Ski Federation
GE	Gross efficiency
GNSS	Global navigation satellite system
HR	Heart rate
HR_{max}	Maximal heart rate
IMU	Inertial measurement unit
P_g	Power against gravity
P_{prop}	Propulsive power
P_{rr}	Power against rolling resistance
PHV	Peak hight velocity
RPE	Rate of perceived exertion
$\dot{V}O_{2dem}$	Oxygen demand
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen consumption reached in a given exercise mode or test protocol
TT	Time trial
TT_{3min}	3-min time trial
XC	Cross country
ΣO_{2def}	Accumulated oxygen deficit

1.2 Explanations

This list contains expression related to this thesis.

"Hovedlandsrennet"	The (unofficial) Norwegian national championship for 14-15-year-olds.
Distance	In this thesis, this is related to the distance that the adolescents raced in "Hovedlandsrennet": All 14-year-olds and 15-year-old girls: 5 km and a duration of ~12-16 min; 15-year-old boys: 7.5 km and a duration of ~19-20 min.
G2	Gear 2, mainly an uphill XC skiing sub-technique. Also used in acceleration from a stationary position. Also called V1 or "padling" in Norwegian.
G3	Gear 3, a XC skiing sub-technique most often used on moderate to large inclinations and in end-spurts. Also called V2 or "dobbeldans" in Norwegian.
G4	Gear 4, a XC skiing sub-technique mainly used on flat and slightly downhill terrain. Also called V2A or "enkeldans" in Norwegian.
Misc.	In this thesis, this refers to the sub-techniques used when free skating, and turning techniques without the use of poles.
Sprint	In this thesis the term is related to the sprint race for adolescents in "Hovedlandsrennet": ~1 km and a duration of ~2.5-3 min for all age groups.

2 Introduction

Cross-country (XC) ski racing is a complex and demanding racing format in which the skiers face large fluctuations in speeds, imposed by the topography of the course, which induce highly varying exercise intensities and complex interactions in energy system contributions [1] and repeated transitions between sub-techniques combining upper and lower body high-intensity effort [1-4]. Thereby, XC skiing places considerable demands on a variety of physical attributes including aerobic and anaerobic power, strength, speed and endurance, as well as technical and tactical expertise [5].

XC skiing has helped researchers to understand the mechanism and limits of human endurance performance [5] and there is a substantial body of research in the field of XC skiing regarding demands and determinants of performance [1-3,5-18], but most of these studies have included recreational, well-trained or elite junior and senior (male) skiers. Less is known for adolescent XC skiers, and the knowledge of the determinants of XC skiing performance in senior skiers cannot simply be scaled down and applied to adolescent skiers.

XC skiing is one of the most popular sports in Norway, with a great number of young skiers participating in organized and unorganized training sessions and races all over the country. At the age of 14 and 15 years, skiers can participate in their first (unofficial) national championship, where almost 550 boys and 350 girls participate in both distance and sprint races. These races are 5 km for 14-year-olds and 15-year-old girls (~12-16 min) and 7.5 km for 15-year-old boys (~19-20 min), as well as sprint races of around 1 km (~2.5-3 min). The boys and girls race the same distances up to the age of 15 years and although these skiers race shorter distances compared to senior skiers, they often race on similar racecourses.

The development process of adolescent XC skiers is multifaceted and challenging, and a complementary mix of athletic attributes has to be acquired and refined [19]. This includes physiological attributes such as a high energy turnover [10,17,20] and efficient movement economy [20,21]; applying tactics in racing situations [19]; and the ability to learn training methods, tactics and technique. XC ski training consists of a substantial amount of on-snow and roller ski specific training [22] and given the complex and demanding nature of XC skiing and the lack of research in adolescent XC skiers, a holistic approach to explore the determinants of ski-specific performance in male and female adolescent skiers is warranted. Better understanding of these determinants in adolescent XC skiers could provide important insights for optimizing the training process and the design of performance tests for adolescent XC skiers.

2.1 Physiological determinants of performance in XC skiing

Competitive XC-skiing involves complex whole-body movements where the goal is to complete a known course in the shortest time possible. The performance in XC ski races is mainly determined by the metabolic energy turnover (energy · time^{-1}) divided by the energy of cost of locomotion (energy · distance^{-1}) (work economy) (Fig. 1). Accordingly, a greater metabolic energy turnover and/or improved work economy will thus improve race performance. Key physiological determinants of performance include peak oxygen uptake ($\dot{V}O_{2peak}$) [10,17,20], the ability to efficiently transform metabolic energy into speed (work economy) [20,21] and the ability to repeatedly perform, and recover from, efforts above the maximal aerobic power [1]. Moreover, the difference in racing distances (durations can vary between ~3 min and ~2 h) places somewhat different anthropometrical and physiological demands on the skiers [11]. Depending on the race length, sub-technique used and technical abilities of the skiers, a certain level of strength also seems necessary to optimize performance [23].

The key physiological determinants of performance observed in junior and senior skiers are most likely also important for adolescent skiers. However, anthropometric, physiological, and biomechanical differences between adolescent and senior skiers exist. As there is a lack of research in adolescent skiers, it is uncertain how these determinants affect skiing performance in male and female adolescent competitive skiers.

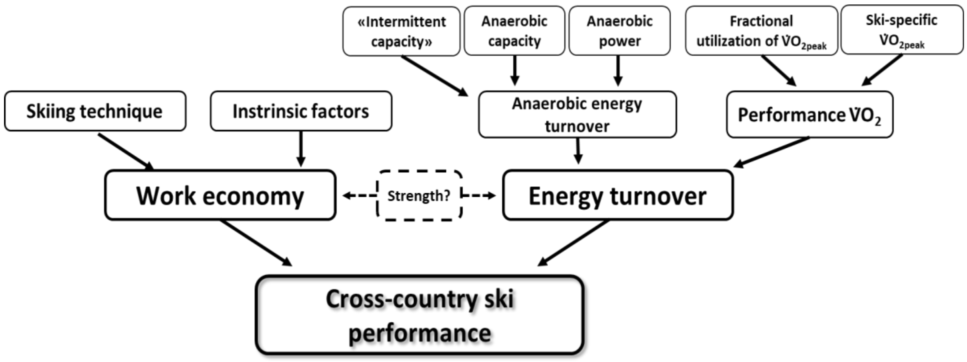


Figure 1. An illustration of key physiological determinants (+ technique) of XC ski performance. See text for details. Modified from Basset & Howley(2000) [24] and Joyner & Coyle (2008) [25]

2.1.1 Energy turnover and work economy

Total energy turnover during endurance competitions is in general determined by $\dot{V}O_{2peak}$ and the fractional utilization of $\dot{V}O_{2peak}$ (performance $\dot{V}O2$) and the anaerobic energy turnover [24,26] (Fig. 1). World-class XC skiers exhibit some of the highest $\dot{V}O_{2peak}$ values ever reported [10,27] and $\dot{V}O_{2peak}$ is considered as a key determinant of XC skiing performance in senior [10,11,16,17,20,28] and junior skiers [29]. Peak oxygen uptake ($\dot{V}O_{2peak}$) is also a major component of performance in high-level adolescent skiers [30], but the development in $\dot{V}O_{2peak}$ seems to be proportional to the growth of fat-free mass (FFM) in both boys and girls [31,32]. The role of $\dot{V}O_{2peak}$ in adolescent XC skiing performance may therefore be more complex than in older and more mature skiers.

Anaerobic capacity is shown as a determinant of XC skiing performance in senior skiers [9], but adolescents have been reported to have lower anaerobic capacity relative to body weight than adults [33] and it is uncertain how anaerobic capacity affects adolescent skiing performance. Recent research suggests that the ability to repeatedly perform, and recover from, efforts above the maximal aerobic power is important for XC skiing performance (“intermittent capacity” in Fig. 1) [1,2]. Furthermore, anaerobic power may affect performance in certain parts of the race like starts and finishes. Hence, the anaerobic capacity per se might not reflect skiing performance, but rather the ability to repeatedly use and recover the energy reserves represented by the oxygen deficits [1]. This ability is, however, currently not known in adolescent skiers.

XC skiing economy is affected by intrinsic factors [34] and an efficient technique to transform metabolic energy efficiently into speed [20,35]. Improved XC skiing economy is shown to improve performance [20,36] and to be a discriminating factor between different ages and performance levels in skiers [37]. However, a recent study in senior male skiers did not find a correlation between skiing economy and outdoor skiing performance [16]. The complexity of the skiing techniques and thereby a possibly large inter-individual variation in technical solutions, together with the influence of intrinsic factors [34], may diminish the discriminating effect of skiing economy on performance [10,16]. No study has explored skiing economy in adolescent skiers; however, a longitudinal study in runners shows that running economy improves rapidly through late childhood/early adolescence, but seems to slow down around the age of 15 years [38]. A previous study did not find a change in skiing economy through the junior years, but it seemed to improve when entering the senior class [29]. In addition, work economy does not seem to predict future success in young athletes [29,39].

2.1.2 Strength

Strength is observed as a potentially important part of the performance puzzle in XC skiing [40,41]. As endurance performance is mainly determined by an athlete's $\dot{V}O_{2peak}$, anaerobic energy turnover, work economy and fractional utilization of $\dot{V}O_{2peak}$, any effect of strength training should be through changes in one or more of these determinants (Fig. 1). Increased strength does not normally affect maximal oxygen uptake ($\dot{V}O_{2max}$) but may potentially increase the ski-specific utilization of the $\dot{V}O_{2max}$ ($\dot{V}O_{2peak}$) [40]. Greater muscle mass affects the anaerobic capacity [42], and thereby XC skiing performance in senior skiers [9], but it is uncertain how this relates to adolescent skiers as adolescents have been reported to have lower anaerobic capacity relative to body weight than adults [33]. Early studies investigating the effect of strength training on skiing performance proposed that strength training enhanced the skiing economy and thus performance [43,44]. However, the relationship between increased strength and improved skiing economy was later questioned, and weaker skiers do not appear to have a greater positive effect of strength training than stronger skiers [23,45]. The effect of inclusion of strength training for XC skiers remains uncertain as the importance of strength seems technique-dependent [15] and substantial individual variation exists in the utilization of increased strength due to the complex quadrupedal XC skiing techniques [23].

A well-developed upper-body power in XC skiing is important from an early age [47] and strength has been shown to correlate with XC skiing performance in adolescent skiers [48] and may be related to improved sport-specific technique in adolescent athletes in different sports [49]. Furthermore, in adolescent skiers, growth in muscle mass, and thereby strength, is an explanatory variable associated with maturity status [46].

2.2 Sex differences

The sex difference in endurance performance in general is approximately 8–12% [50]. The physical advantage of male compared to female athletes emerges during early adolescence, coinciding with the onset of male puberty (~12–13 yrs) [51] and throughout adolescence, the sex difference in endurance performance approaches the sex difference observed in senior athletes [52,53]. The timing of puberty differs between boys and girls, as girls mature before boys [33]. In XC skiing, the estimated peak height velocity (PHV, a measure of adolescent growth spurt that coincides with the onset of puberty) in male XC skiers has been estimated to be between 13.8 [31] and 14.2 years [54,55] compared to ~12.2 years for female skiers [31,48] and maturity status has previously been found to be a major confounding variable for performance in boys of 13.8 years, but not in girls of 13.4 years [48].

In XC skiing, male skiers typically perform 10–12% better compared to their female counterparts [8,50] depending on the sub-technique employed, since the sex difference is magnified when the contribution from poling increases [15]. When analyzing the results from the last three years in the national championships for 14-year-olds ("Hovedlandsrennet") the mean time of the top three boys was 11% faster than the mean time of the top three girls in both sprint and distance racing. The mean time of the top three girls would be around the top 30% mark in the boys' ranking for both sprint and distance (www.skiforbundet.no).

The physiological sex difference is driven by sex-specific changes in circulating levels of hormones during puberty, as circulating testosterone concentrations rise in men due to a 30-fold increase in testosterone production [56], which in turn results in greater muscle mass, lower relative body fat and a higher concentration of red blood cells and total red blood cell mass in men compared to women [50].

$\dot{V}O_{2peak}$ appears to be a major determinant for the sex difference in endurance performance [50] and a sex difference of ~10-15% is typically reported in elite endurance athletes when expressed relative to body weight [57]. However, male junior and senior XC-skiers achieve

~20% higher $\dot{V}O_{2peak}$ relative to body weight compared to female counterparts when skiing [8,58]. The reason for this discrepancy is currently not known, but it has been suggested that a larger upper-body muscle mass [50] and a more effective utilization of upper-body strength in men compared to women can explain some of the differences [15]. However, the ski-specific $\dot{V}O_{2peak}$ relative to running (e.g., $\dot{V}O_{2peak}$ in double poling vs. running) does not seem to be different between sexes or performance levels [18]. XC ski-specific sex differences in $\dot{V}O_{2peak}$ relative to body weight for adolescent skiers have not been previously reported, but a sex difference in $\dot{V}O_{2peak}$ of ~11-12% in adolescent skiers aged 12-15 years while running has been observed [31].

For anaerobic capacity the sex difference is ~30% [10,11] and can primarily be explained by the relatively larger muscle mass in men and the difference in working muscle mass [42]. The sex difference in anaerobic capacity in senior XC-skiers has not been calculated in the same study, but has been reported to be ~16% larger in male junior XC-skiers compared to their female counterparts [58]. Furthermore, the ability to convert the rate of metabolism into work and speed is important in a sport such as XC-skiing, with complex whole-body techniques, but there seems to be no sex difference in work economy in senior XC skiers [59,60]. The sex difference in ski-specific anaerobic capacity and work economy in adolescent skiers is not known.

2.3 Pacing

The ability of athletes to decide how and when to invest their energy resources during the race (i.e. pacing) can have a significant impact on performance [61,62]. It is suggested that pacing is a combination of anticipation, knowledge of the end-point, prior experience and sensory feedback [63] and there is a variety of models and theories attempting to explain the regulation of exercise intensity, highlighting the complexity of pacing [64]. Physical maturation, the development of cognitive functions, and the accumulation of experience with exercise tasks, play a major role in optimizing pacing for adolescent athletes [65-67]. Hence, the learning process for pacing optimization can be of great importance in the development and future performance of adolescent skiers [68].

In XC ski races, skiers face large fluctuations in speeds, imposed by the topography of the course, which induce varying exercise intensities and repeated transitions between sub-techniques [1-4]. This clearly challenges the skiers' ability to prescribe their exercise intensity, thus making pacing important for successful performance. XC-skiers normally apply a positive pacing strategy (i.e. reducing speed) on a lap-to-lap basis irrespective of distance, technique or sex, with a typical decrease in speed of 2-12% during competitions [69]. Within laps, recent studies demonstrate that skiers also perform a variable pacing pattern due to the undulating terrain [1,2].

Adding to the complexity of pacing in XC-skiing, accessible tools to monitor exercise intensity, such as heart rate monitors, do not reflect the rapid fluctuations in exercise intensity during races [2,8,70] and cannot be used continuously during a race to plan, adjust or to evaluate the pacing. Therefore, the acquisition of pacing skills during a race is subject to a trial and error type of learning. Evidently, as level of expertise affects pacing, better skiers seem to maintain their speed to a greater extent compared to slower skiers throughout distance time trials (TTs) [62,71]. In addition, older and thereby more experienced skiers seem to distribute their effort in a manner that allows better performance compared to less experienced skiers with the same physiological capabilities [72,73,74]. Senior athletes also have a more developed aerobic endurance and anaerobic capacity than young athletes [75,76] and it is not clear whether adolescent skiers have similar abilities regarding pacing to those observed in senior skiers.

2.4 XC skiing biomechanics

2.4.1 XC skiing sub-techniques

One of the pillars of endurance performance is the ability to transform metabolic energy efficiently into speed [20,35]. In XC skiing, this is coupled with an “efficient technique”, which can be defined as “the relative position and orientation of body segments as they change during the performance of a sport task to perform that task effectively” [77]. Competitive XC-skiing consists of two separate techniques (classic style and free style; called skating) each with several sub-techniques. The sub-techniques act as a gearing system where the skiers can freely choose the preferred technique to match the demand of the external conditions and to optimize performance (Fig. 2) [78].

This thesis focuses on skating techniques, for which the primary sub-techniques include G2, G3, G4, and free skating without poles (G5 in Fig. 2) [79]. In addition, a turning technique used around corners and a tucked gliding position (TP) when speed is high are often used.

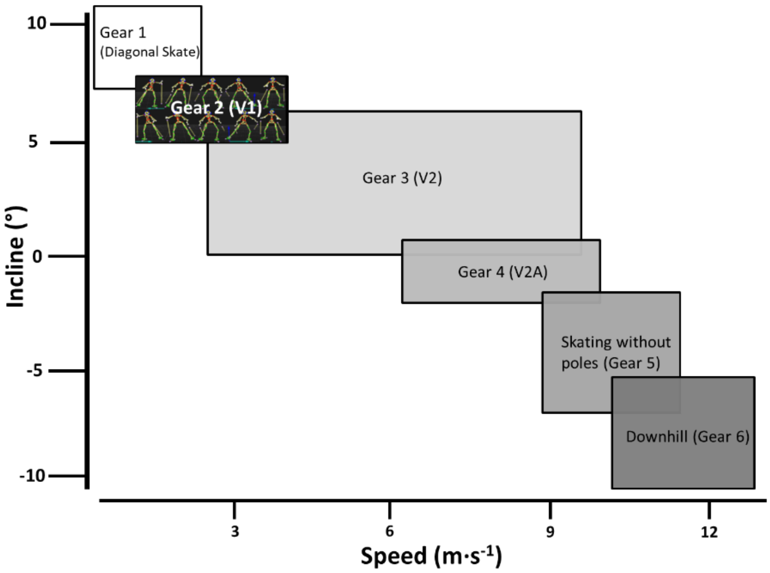


Figure 2. Illustration of the gear system in free style (skating). The figure is taken with permission from Losnegard (2019) [18]. The illustration is further based on Andersson et al. (2010) [3], Gløersen et al. (2018) [80], Losnegard et al. (2012) [34] and unpublished data from our lab. The Gear 2 sub-technique was used in the treadmill roller skiing in the present research project.

The skiers in the present research project performed the G2 sub-technique on the treadmill in **papers I-II** and **IV**. G2 is considered an uphill technique used on moderate to steep inclines and is characterized by asymmetrical use of the upper body in one asynchronous double poling action per cycle time with one of the skating strokes (strong side), but not on the other side (weak side). Skiers usually have a preferred side for the poling action (dominant side). Using the poles on the opposite side to the preferred side is referred to as using the non-dominant side. Faster skiers exhibit better synchronized poling, more symmetric edging by and forces from the legs, and are more effective in transforming the resultant forces into propulsion during G2 [81]. The largest proportion of time in XC ski races is spent in uphill sections and uphills are the most discriminating sections during races [3,8,70]. It is thus reasonable to assume that improved uphill technique will also improve overall performance.

2.4.2 Choice of sub-techniques

Speed is the main factor affecting the choice of gears [79] (Fig. 3). Therefore, faster skiers demonstrate more use of "high-speed gears" compared to slower skiers during competitions. [8,71]. Two major factors affecting speed are the physiological capacity of the skier and the external braking forces [82]. To maintain a certain speed, skiers must overcome the braking forces from external conditions through the generation of propulsive force from poles and skis, while preferably minimizing the expenditure of metabolic power [83]. Furthermore, skiers need to adjust their technique to match the conditions so that for a given metabolic cost the greatest speed will be obtained [84]. Individual preferences, influenced by the skiers' experience, beliefs, and knowledge concerning the optimal technique, will also affect technique choice [34]. In modern mass start XC-skiing, speed and pacing are often also affected by the skiers nearby and the skiers' tactical choice.

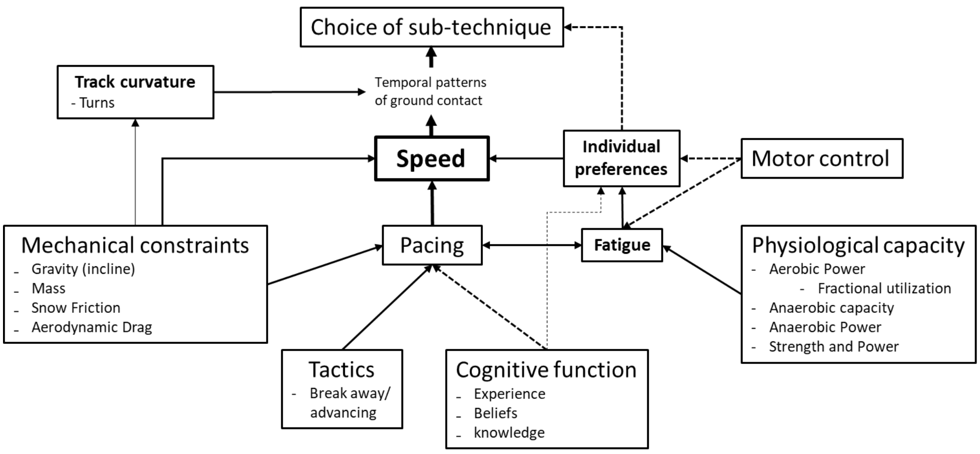


Figure 3. Schematic illustration of key factors affecting the choice of sub-techniques during XC ski races. The speed of the skiers affects the temporal patterns of ground contact, which defines the sub-technique. The main factors affecting speed are mechanical constraints and physiological factors via skiers' pacing during a competition. Other factors such as tactics, thoughts and beliefs (cognitive function) and motor control can also affect the choice of sub-technique. Solid arrows indicate that research has been done on the subject, while dotted arrows indicate that further research is warranted.

Given the large fluctuations in speed during a race, elite skiers normally perform about 15-25 transitions between sub-techniques or "gears" per km [3,4,85] and efficient transitions between gears may improve performance [3]. Thus, gear selection is an important part of pacing and is probably related to the performance level, and may vary with age groups and experience. Although several studies have investigated gear selection in XC skiing [3,4,8], no studies have included adolescent skiers.

2.4.3 Technique training

Since XC-skiing is a sport that involves a complex interaction of different movement patterns in a coordinated manner, it is reasonable to assume that improved technique will also improve overall performance through improved work economy. Key identifiers of efficient sport-specific techniques have been widely studied [77], but less is known about how these are acquired in applied practice settings. Although technique and technique training have been proposed to be among the most important determinants of adolescent skiers' performance development, surprisingly few studies exist on how to best acquire an efficient technique.

Technique training in applied settings aims to implement deliberate practice, which facilitates beneficial technique modifications and results in a more efficient technique and improved performance through improved work economy or higher propulsive forces. In applied youth sport practice settings, this most often occurs in groups with a high athlete-to-coach ratio, which restricts coaches' opportunities to provide individual feedback [86]. Thus, organizing practice sessions to facilitate more individual feedback may be an important aspect of technique training. However, previous research has been based on interaction with a single participant at a time [86] and few ecologically valid feedback studies from applied sport practice settings exist [87].

Despite the well-defined features of the G2 technique, the most effective movement patterns are not identical between XC-skiers, although skiers reproduce their individual patterns over time [88]. Furthermore, technique modifications need to facilitate increased performance (or fewer injuries) to have relevance for the athlete. An approach to overcome these challenges is to follow the same skiers during a training period and implement performance tests to determine whether technical alterations enhance performance.

2.4.4 Feedback and observation

Augmented feedback is one of the most important features in acquiring and improving sport-specific technique [89]. In applied sport practice settings, the coach often provides augmented feedback to facilitate the process of acquiring a more efficient technique. However, a coach does not necessarily provide feedback that facilitates this process optimally [90]. Furthermore, in youth sports, the coach is often a non-professional, such as a parent or other volunteer with limited content knowledge both of efficient sport-specific technique and of how to effectively promote this technique.

Observation of others, or oneself, is frequently used to assist athletes' learning processes in applied sport practice settings [91] and may enhance learning [87,92] as well as increasing learners' motivation [93]. Two observational methods promoting more individual feedback are 1) peer-model observation through dyad practice, where two athletes interactively observe and instruct each other, and 2) conducting self-observation through video [87,93]. Dyad practice may increase cognitive involvement [93], as well as ownership of and responsibility for the learning process, and consequently improve motor learning [94]. Today's smartphones, with large high-resolution screens, may provide practice settings where multiple individuals receive immediate viewable feedback simultaneously [86] with positive performance outcomes [95]. However, the results from using video feedback for performance outcomes have been equivocal [87], implying the need to reduce the information given to young athletes. Therefore, video feedback with attentional cues, where the athlete's attention is directed to the most appropriate aspects of the technique, can accelerate the process of beneficial technique modification [96,97], and has been shown to be superior to video feedback only [98]. Both verbal and visual cueing have been shown to facilitate the acquisition of efficient technique [99]. However, in applied sport practice settings with a high athlete-to-coach ratio, feedback methods with cueing promoting more individual feedback should be explored. As such, written cue cards may give attentional cues to multiple athletes simultaneously in applied sport settings.

2.5 Laboratory vs field measurements

The early pioneering work during the 1980s and 1990s mostly focused on kinematical analyses of the different skiing techniques combined with physiological responses, where researchers explored temporal patterns during on-snow skiing with preselected angles of different body segments and skis and poles (Fig. 4) [100-104]. The quantitative methods used were comprehensive and the data processing was time consuming, but resulted in valuable insights that coaches and skiers could use for better knowledge of the movement patterns during a time period when XC-ski skating technique advanced rapidly.

Much of the cross-country research over the last couple of decades has been performed indoors on treadmills to avoid compromising internal validity, which can be affected by changing weather and snow conditions [9,11,21,34,58,81,105]. Indoor testing secures the combination of continuous physiological and biomechanical data, while keeping internal validity high. Treadmill roller skiing tests provide a good simulation of on-snow skiing as indoor and outdoor performance correlate [13,14,20,106] and the skiing techniques are similar between treadmill and outdoor skiing [107].

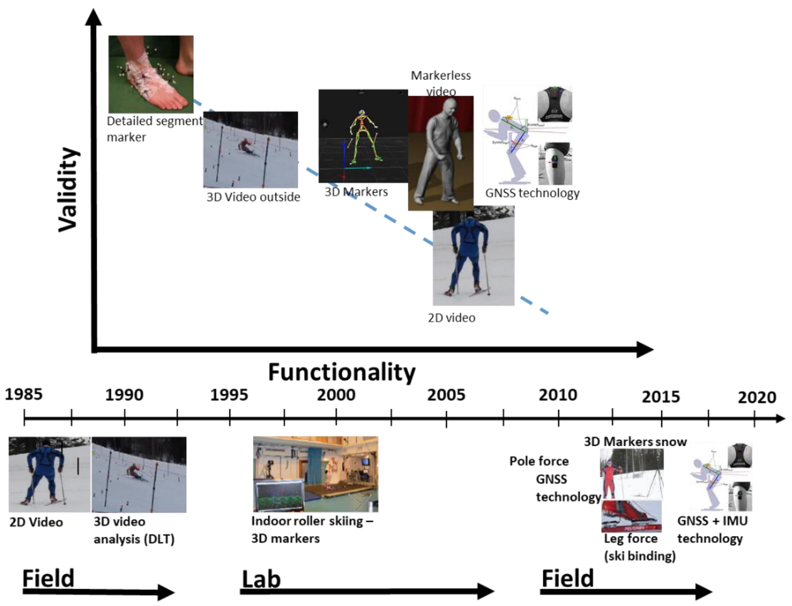


Figure 4. Overview of different methods used for technique analysis, the time periods in which they were introduced and their validity and functionality. Modified from the trial lecture of the doctoral defense of Dr. Håvard Myklebust.

However, real-world on-snow XC skiing performance is more complex than treadmill roller skiing performance due to the topography of the course, tactics, the quality of the equipment, and weather and snow conditions. Furthermore, treadmill roller skiing does not exactly replicate skiing on snow due to different friction coefficients [105] and the absence of air resistance. Indoor testing on a treadmill thus challenges the external validity of a study. In recent years, new technology has emerged using global navigational satellite systems (GNSSs) and inertial measurements units (IMUs), which can be valuable tools for physiological and technical analysis by continuous measure of position, speed and acceleration throughout a race while simultaneously differentiating between different sub-techniques throughout a race [1,108-113]. Using this new technology for outdoor measures, combined with laboratory measures, gives an opportunity for a broader approach and insights into ski-specific performance diagnostics for XC skiers and various skiing personnel.

3 Research aims and hypotheses

Better understanding of how different determinants affect XC skiing performance in male and female adolescent skiers can provide important insights for optimizing the training process and the design of performance tests for this age-group. Given the paucity of ski-specific performance diagnostics in adolescent XC skiers, the overall aim of the present thesis was to explore determinants of XC ski performance in male and female competitive adolescent skiers.

The specific aims were to:

I. Investigate how anthropometric and key physiological determinants of XC ski performance explains and correlate with laboratory and outdoor skiing performance (**papers I - II**).

II. Investigate the sex difference in anthropometric and key physiological determinants of XC skiing performance and compare this sex difference with the sex difference in junior and senior skiers (**papers 1-II**).

III. Investigate the pacing patterns, and thereby exercise intensity and sub-technique selection, in male adolescent XC skiers (**paper III**).

IV. Investigate the effect of observational feedback, providing more individual feedback in groups with a high athlete-to-coach ratio, compared to coaching feedback on XC ski performance (**paper IV**).

Main hypotheses

I. **Paper I** was an exploratory study, but we expected that $\dot{V}O_{2peak}$ would be a key determinant of adolescent skiing performance and that the importance of the different physiological determinants would be similar to that of senior skiers.

II. **Paper II** was an exploratory study, but we expected that the juniors and seniors would show similar sex differences in performance, but that the sex difference in performance between adolescent boys and girls would be slightly smaller by comparison with the older age groups. We further expected that the sex differences in $\dot{V}O_{2peak}$ would be a key determinant of the sex differences in performance.

III. **In paper III**, we hypothesized that the adolescent skiers would apply a variable pacing pattern, with a more pronounced positive pacing pattern compared to the senior skiers. We also hypothesized that the lower speeds applied by the adolescent skiers would induce more use of lower gears compared to the seniors.

IV. **In paper IV,** we hypothesized that coaching feedback would lead to the greatest improvement in high-speed performance and work economy, but that video feedback and dyad practice would be alternatives that would improve both high-speed performance and work economy.

4 Methods

4.1 Study ethics

The studies were approved by the ethics committee at the Norwegian School of Sport Sciences, found advisable by the Norwegian centre for Research Data, and conducted according to the Declaration of Helsinki (Appendix 5-7). All skiers were informed about the potential risks and discomforts associated with the studies and gave their informed written consent to participate. Written parental consent was also obtained for skiers younger than 18 years. In addition to the written information, the general outlines of the studies were explained orally to all subjects before inclusion. All subjects could withdraw their consent at any time, and this was especially emphasized to the skiers younger than 18 years. Special considerations were taken for the skiers younger than 18 years. They got their own information letter using plain language, they could bring their parents to the test site, however, only the researchers were together with the skiers when testing in the laboratory.

4.2 Participants

In total, 29 male and 29 female adolescent competitive XC skiers volunteered, with some skiers participating in several studies. Further, a total of 8 male and 7 female elite junior skiers and 15 male and 6 female senior skiers participated. The participants' characteristics are summarized in Table 1. The adolescent and junior skiers were recruited from local skiing clubs, while the seniors were skiers living in the region and were contacted directly.

Table 1. Participants' characteristics in the four studies.

Paper	Age-group	Sex	n	Age (yrs)	Height (cm)	Body-weight (kg)	$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	Total training ($h \cdot week^{-1}$)
I	Ado.	M	27	14.7 ±0.6	172 ± 7	57.2 ± 7.7	62.1 ± 5.6	9.3 ± 3.6
		F	25	14.8 ± 0.5	167 ±5	56.6 ±7.8	53.9 ± 5.9	8.9 ± 3.2
II	Ado.	M	8	15.0 ± 0.4	177 ± 8	64.3 ± 5.9	66.3 ± 4.3	12.8 ± 3.4
		F	12	14.7 ± 0.6	165 ± 4	54.9 ± 6.1	56.7 ± 6.5	9.7 ± 2.6
	Jun.	M	8	17.6 ± 0.7	181 ± 5	69.7 ± 5.8	69.3 ± 4.8	11.7 ± 2.0
		F	7	17.6 ± 0.6	168 ± 5	61.1 ± 6.1	57.1 ± 4.6	10.6 ± 1.2
	Sen.	M	7	27.9 ± 4.9	178 ± 5	73.8 ± 6.2	77.5 ± 3.9	18.6 ± 1.7
		F	6	27.8 ± 3.3	170 ± 5	63.4 ± 5.8	65.2 ± 6.5	16.5 ± 1.9
III	Ado.	M	11	14.4 ± 0.5	---	58.9 ± 7.3	63.9 ± 2.8	---
	Sen.	M	8	22.6 ± 4.3	---	77.1 ± 5.3	77.4 ± 4.4	---
IV	Ado.	M	27	14.2 ± 0.6	172 ± 7	57.2±7.7	61.9±5.6	9.3±3.6
		F	27	14.3 ± 0.6	166 ± 5	55.9±8.1	53.5±5.8	8.6±3.2

Note; Data are mean ± SD, $\dot{V}O_{2peak}$ = maximal ski specific oxygen uptake, $\dot{V}O_{2peak}$ calculated from G2 treadmill rollerskiing 3-min time-trial, Ado = adolescents; Jun. = juniors; Sen. = seniors, M = male; F = female

4.2.1 Performance level

The adolescent skiers in **paper I** and **paper IV** were all competitive XC skiers, but no specific performance level was required as an inclusion criteria. The skiers in **paper I** and **IV** thus represented performance levels from top international performance level to lower-ranked national performance level. The best adolescent skiers from **paper I** also participated in **paper II.** The performance level was calculated from the only national competition available to them during the season ("Hovedlandsrennet", unofficial national championship). Skiers can compete in this race for two consecutive years (age 14 and 15) and the performance level was calculated from the mean of these two races. The performance level was calculated as the percentage behind the mean time of the top three skiers in "Hovedlandsrennet". In **paper II**, to match for performance level, we included all skiers who were on average less than 10% behind the mean time of the top three skiers in "Hovedlandsrennet" (boys 9% and girls 7% behind the mean time of the top three).

For the junior skiers in **paper II**, the performance level was calculated in a similar manner as for the adolescents. The performance level for the juniors was calculated from their three best distance races during the Norwegian national cup in the season nearest to the testing (men 7%

and women 9% behind the mean time of the top three). Four of the junior skiers (two male and two female XC skiers) were part of the Norwegian Junior National XC skiing team and had in total four medals from the FIS Junior World Ski Championships. The male and female juniors were matched for performance via previous results in the national XC skiing cup.

The performance level for the senior skiers in **paper II** was based on FIS points at the current time of testing (FIS, 2019). The senior skiers were considered world-class (men 16 and women 19 FIS points). Men and women combined had won a total of 25 world championship gold medals (men n = 3, women n = 3), seven Olympic gold medals (men n = 2, women n = 4), and 115 individual world cup victories (men n = 5, women n = 4), at the end of the 2018/2019 season. There was one world-class biathlon athlete in the group, who had also performed at an international level in XC skiing.

The eleven adolescent boys who volunteered for **paper III** also participated in **paper I** and **paper IV,** and some in **paper II,** and placed between 20th and 167th in ~300 participants in "Hovedlandsrennet" in their respective age groups. The eight senior skiers in **paper III** had an FIS point range of 13-117 (Norwegian national rank 9-278) and were also part of a previous study [1].

4.3 Experimental overview papers I-II

The adolescent skiers completed two familiarization sessions before the main test session, the juniors completed one familiarization session, and the senior skiers completed all testing in one main test session (Fig. 5). The skiers performed submaximal and maximal uphill treadmill rollerskiing in the G2 skating sub-technique. Gross efficiency (GE) was calculated from a submaximal work bout (~84% of $\dot{V}O_{2peak}$) at a 6° incline while $\dot{V}O_{2peak}$ and maximal accumulated oxygen deficit (ΣO_{2def}) were established from a 3- min time trial (TT_{3min}) at 8° incline. In addition, 15-s maximal skiing power (P_{max}) was calculated from an incremental treadmill speed test (used in **papers II** and **IV**), before upper- and lower-body one-repetition maximum (1RM) strength tests were performed. In **paper I**, correlation and multiple regression analysis were performed to explore the relationship with anthropometrical and physiological determinations ($\dot{V}O_{2peak}$, ΣO_{2def}, GE and strength) of performance with both the laboratory and on-snow sprint and distance performance from the unofficial national championship for this age group. In **paper II,** the sex differences in $\dot{V}O_{2peak}$, ΣO_{2def}, GE and strength within adolescent (~15 years), junior (~18 years) and senior (~28 years) XC skiers were explored. All adolescent skiers were tested during the same period of the year (August-September).

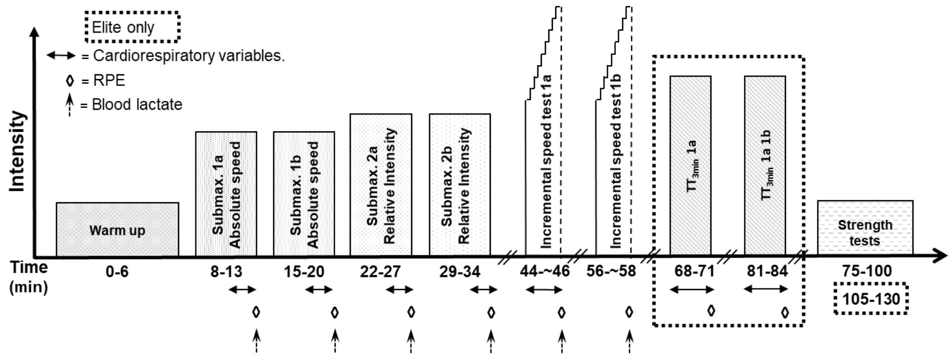


Figure 5. Overview of the main test session. Not shown in the figure or included in the thesis are kinematical measures taken from 60-100 s.

4.4 Experimental overview paper III

The skiers completed two (seniors) or three (adolescents) test sessions, separated by 16.8 ± 6.3 days. The first session consisted of an individual free technique roller ski TT performed on the same international racecourse for both groups. Seniors raced 13.1 km (2x4.4 km + 4.3 km) and adolescents raced 4.3 km to simulate the normal age-related racing distances the two groups are used to completing in real competitions. The reason for the discrepancy in lap lengths between groups was due to the ~100 m extra distance when starting a new lap. Throughout the TT, position and speed were measured using a standalone GNSS receiver mounted on the skier. The second session was a laboratory session on a roller skiing treadmill, where the individual cost of transport (*C*) during submaximal loads for different speeds and inclinations was assessed for both groups. $\dot{V}O_{2peak}$ and ΣO_{2def} were measured after the submaximal loads for seniors, while this was performed in a separate session for adolescents. Individual exercise intensity, expressed as oxygen demand ($\dot{V}O_{2dem}$), was calculated for different segments of the course, assuming a linear relationship between *C* and the propulsive force (F_{prop}) [1]. F_{prop} was calculated from the standalone GNSS receiver position measurements collected during the TT, combined with a model for air drag and differential carrier-phase GNSS measurements of the ski course. Classification of each skier's gear selection throughout the TT was achieved by visual inspection of gyroscope and accelerometer signals from an inertial measurement unit (IMU) mounted on the skier, in combination with the position and speed of the skier on the course.

4.5 Experimental overview paper IV

The skiers performed two familiarization sessions before the main test session pre-intervention, identical to that described in papers I-II (Fig 5). During the 5-week intervention period the athletes performed 6x ~30 min practice sessions on rollerskis using the G2 technique on the non-dominant side, before a new main test session post-intervention (Fig. 6). The performance testing pre- and post-intervention was performed on a rollerski treadmill and performance outcomes were the change scores from pre- to post-intervention in maximal power output relative to body weight from an incremental speed test, and skiing economy during submaximal rollerskiing. The skiers were divided into a control group and three intervention groups. The feedback methods during the intervention were Dyad practice (DYAD), Video feedback (VIDEO), and feedback from an expert coach (COACH). The control group (CON) performed only the main test sessions pre- and post-intervention, with no intervention practice sessions in between. The intervention groups used identical attentional cue cards to control the content of feedback information (Table 2). The timing, frequency and amount of feedback were identical between groups.

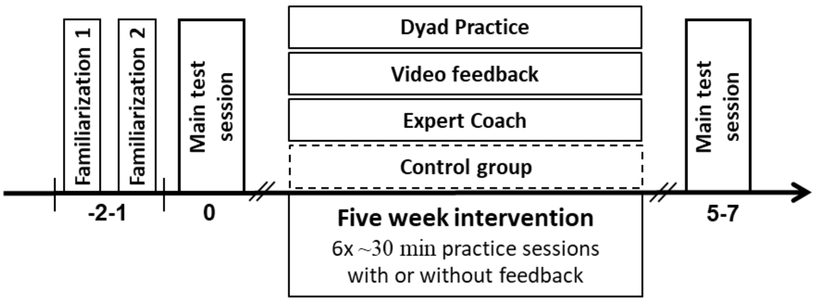


Figure 6. Overview of the intervention period in paper IV. The familiarization and main test session were identical to those described in papers I-II.

4.6 Instruments and materials

Laboratory tests were performed on a roller skiing treadmill with belt dimensions 3 x 4.5 m (Rodby, Södertälje, Sweden). All athletes used roller skis (Swenor, Sarpsborg, Norway) they were accustomed to (junior and senior: Swenor Skate Long, length 630 mm, weight 795 $g\cdot ski^{-1}$; adolescents: Swenor Skate; length 580 mm, weight 705 $g\cdot ski^{-1}$). For the treadmill tests skiers used the same roller ski wheel type with the same coefficient of rolling resistance (C_{rr}, $\mu = 0.018$) (Swenor, wheel type 1) and Rottefella binding systems (Rottefella AS, Lier, Norway) except for submaximal work bouts to calculate C in **paper III** (Swenor, wheel type 2, Swenor Skate Long 0.0225 ± 0.0009; Swenor Skate 0.0215 ± 0.0004) (see methodological considerations). The friction was checked every week throughout the study period and was consistent throughout the test-period. Each skier used the same pair of roller skis on all tests. The C_{rr} for each pair of roller skis used during the tests was measured prior to the study using a towing test on the roller skiing treadmill as described previously [114]. During laboratory tests, all participants used Swix Triac 3.0 or Swix Triac 1.0 poles with self-selected length (~90% of body height) (Swix, Lillehammer, Norway), modified with a tip specially adapted for use on a roller skiing treadmill. The participants were secured to the treadmill with a safety harness connected to an emergency brake during testing. Athletes used their own ski poles on the TT in **paper III**. In **paper IV**, the skiers used their own equipment during practice sessions.

Oxygen consumption was measured using an automatic ergospirometry system (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany). The Oxycon Pro Jaeger Instrument was calibrated according to the instruction manual as described in detail previously [40]. Breath-by-breath and mixing chamber mode were also used (see methodological considerations). Blood samples were taken from a fingertip after each 5-min bout and were analysed for the determination of blood lactate concentration (Biosen C-line, EKF diagnostic GmbH, Magdeburg, Germany). The Biosen system was calibrated with a standard solution of lactate (12 mmol L^{-1}) prior to the analysis. Body mass and total mass including equipment were measured before each testing session (Seca model 877, Hamburg, Germany). Heart rate was recorded with the same heart rate monitor on all tests, measuring at 1 Hz (Polar M400, Kempele, Finland). Rating of perceived exertion (RPE) was evaluated using the Borg scale (6-20) [115] directly after each 5-min steady-state load.

In **paper III**, a 10 Hz standalone GNSS-receiver (Catapult Optimeye S5, mass 67 g, firmware version 7.18, Melbourne, Australia) with a 9-axis IMU (accelerometer, gyroscope and magnetic field measurements) was used for position and speed tracking, for F_{prop} calculations, and for inspection of accelerometer and gyroscope signals for gear classification during the TT. Methodological details can be found in Gløersen et al. (2018) [80].

4.7 Procedures

4.7.1 Papers I-II

4.7.1.1 G2 skating sub-technique

All the treadmill skiing measures were performed in the XC skiing sub-technique G2 except for the tests for *C* in **paper III**. (See the description of XC skiing sub-techniques later.) All skiers participating had a clear-cut opinion of which side was dominant and which was non-dominant in the G2 sub-technique (Fig. 7).

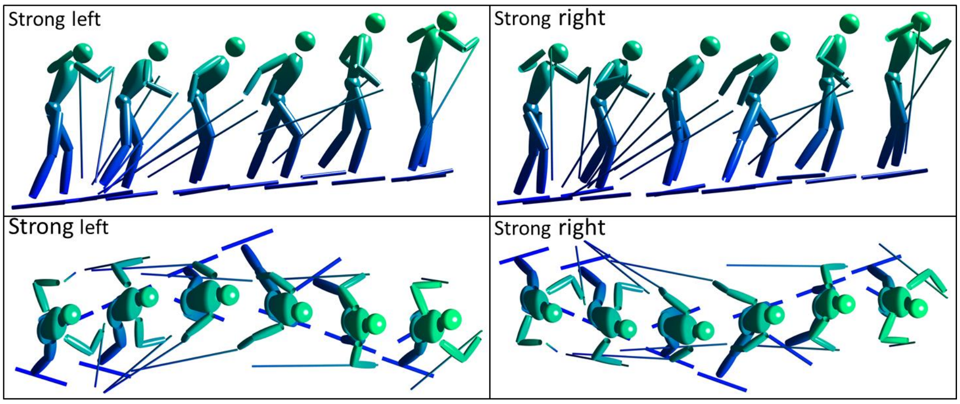


Figure 7. One full cycle for the G2 skating sub-technique starting with pole plant on the strong side. Upper panels show a side view and bottom panel shows a top view.

4.7.1.2 Familiarization

All the adolescent skiers participating in this project completed two familiarization sessions in which they became well accustomed to the treadmill and the different tests, using the same apparatus that they were to use during the main test session (Fig. 5). The first familiarization consisted of 30 min submaximal rollerski skating before completing two incremental speed tests (see later). The adolescent skiers became familiarized with the treadmill, as seen in the absence of difference in performance from the last familiarization session to the pre-intervention main test session for the speed test (difference of 0.1 ± 1.1%).

The second familiarization session consisted of a 10-min easy self-paced warm-up and two five-min submaximal G2 work bouts with cardiorespiratory measurements for familiarization to the equipment before performing a 3-min maximal time-trial (TT_{3min}). After the treadmill session, they familiarized themselves with the strength tests (see later). The junior skiers in **paper II** were well accustomed to the treadmill through previous testing and performed only one familiarization to familiarize with the incremental speed test and strength tests and perform the TT_{3min}. The senior skiers in **paper II** were used to similar test set-ups through years of laboratory testing and due to time restrictions, they performed all tests in one session.

4.7.1.3 3-min Time Trial (TT_{3min})

TT_{3min} was used in all four papers. The senior skiers in **paper II** performed the TT_{3min} as part of the main test session (Fig. 5). TT_{3min} was a 3-min maximal uphill time trial at 8° incline in the G2 sub-technique. The starting speed was 2.0 $m \cdot s^{-1}$ for the adolescent girls, 2.25 $m \cdot s^{-1}$ for the adolescent boys and junior women, 2.5 $m \cdot s^{-1}$ for the junior men and senior women, and 2.75 $m \cdot s^{-1}$ for the senior men. The speed was fixed during the first 30 s to prevent the skiers from starting too fast. The skiers controlled the speed by adjusting their position on the treadmill relative to laser beams situated in front of and behind the skier. Each contact by the front wheels with the laser induced either an increase or a reduction in speed by 0.25 $m \cdot s^{-1}$ conducted manually by the test leader. Visual feedback with respect to time was provided to the subjects, and a separate monitor allowed the test leader to follow the subject's motion. Cardiorespiratory variables ($\dot{V}O_2$ and RER) were monitored throughout the test and analyzed for $\dot{V}O_{2peak}$ and ΣO_{2def}. The performance outcome from the test was the distance covered. $\dot{V}O_{2peak}$ was defined as the highest rate of oxygen consumption averaged over the six highest consecutive 5-s measurements (total 30 s) from TT_{3min}.

4.7.1.4 Main test session

The main test session was performed in **papers I-II** and **IV** (Fig. 5). An easy self-paced 6-min warm up, 3 min on the dominant and 3 min on the non-dominant side, was completed using the G2 technique before completing four 5-min submaximal work bouts. Whether the skiers started with the dominant or non-dominant side was randomized. Thereafter the skiers switched between sides for each work bout (between a and b in Fig. 5). In **paper IV** the adolescent skiers used identical test protocols before and after the intervention. The two first 5-min steady-state work bouts were performed at the same speed and incline (2.0 m/s, 6°

incline for all participants; 1a and 1b in Fig. 5). The results from the first two 5-min steady-state stages are not discussed in this thesis. Thereafter, the skiers completed two new 5-min efforts at a 6° incline at a pace corresponding to the same estimated relative intensity (between 83 – 86% of $\dot{V}O_{2peak}$ for all skiers, 2a and 2b in Fig. 5). GE in **papers I-II** and **IV** was calculated from this work bout. Cardiorespiratory variables and heart rate were monitored from 2-5 min and the averages for 2.5-5 min provided the steady state values used for further analysis. Each 5-min work bout was separated by a 2-min break. Rate of perceived exertion (RPE) (Borg Scale 6-20) was recorded immediately after each stage [115].

4.7.1.5 Incremental speed test (P_{max})

The incremental speed test was used in **paper II** and **paper IV**. The test was performed 10 min after the last submaximal work bout and was similar for all skiers. The test started at an incline of 8° and a speed of 2.5 m/s (estimated O_2-cost of ~66 $ml \cdot kg^{-1} \cdot min^{-1}$) and the speed increased automatically by 0.25 m/s every 15 s (estimated increase of ~7 $ml \cdot kg^{-1} \cdot min^{-1}$). The participants skied between two laser beams projected on to the treadmill in front of and behind them. When the participants could not keep in front of the rearmost laser beam with the front wheels of the roller skis for two consecutive G2 technique cycles, the test was ended manually by the test leader. A separate monitor allowed the test leader to follow the participants' movements. The performance outcome was the maximal 15-s propulsive power (P_{max}) from the test relative to body mass.

4.7.1.6 Strength tests

The 1RM strength tests were performed 20 min after the end of the rollerski tests with the same protocol as that used by Losnegard (2011) [40]. The specific warm-up consisted of 10-6-3 reps at 40-60-80% of estimated 1RM. The first attempt for both tests was performed with a load approximately 5% below the expected 1RM. The rest period between each attempt was 2–4 min. The order of the tests was the same for all participants. Strength was tested on both sides of the body to assess whether there was a difference in strength between the right and left sides. As there were no differences in strength in any groups between left and right arms and legs, the strength numbers presented in this thesis are therefore the average of the left and right side. All 1RM testing was supervised by the same investigator and conducted on the same equipment, with identical equipment positioning for each subject.

Single leg press: The single leg press test was performed on an inclined (45°) leg press machine. Before the test, the correct depth (90° knee angle) was measured and noted. The test started with straight legs before the skiers lowered the weights to the correct depth, at which point they received a signal from the test leader to push back up. The attempt was considered valid when the weights were returned to the starting position.

Single arm pull-down: Seating was adjusted to a 90° angle at the knees and hips, with a “neutral” spine and back resting against a backboard and both feet flat on the floor throughout the test. The “non-testing arm” rested on the opposite thigh. The pull was performed holding a custom-made ski pole grip positioned at the height of the forehead. The wire was parallel to the back support. Participants then pulled the grip straight down, with the pull defined as valid when the hand hit the bench they were sitting on in one continuous motion, without bending the torso forward away from the backboard and with both feet kept on the ground.

4.7.2 Paper III

4.7.2.1 Outdoor test - Time Trial

The TT was conducted in Holmenkollen, Oslo, Norway, with similar topography to the racecourse used during winter competitions (distance 4.3 km, height difference 51 m, maximum climb 32 m, total climb 166 m) (see Fig. 12 for racecourse profile). Before the warm-up, the weight of the athletes including equipment (including roller skis, ski poles, ski boots and helmet) was measured.

Warm-up: Both groups were instructed to complete one lap at an easy pace, before they were given 10 min to warm up as they normally would do before a regular competition.
Time Trial: To simulate normal TT distances for the two groups, seniors were instructed to complete three laps (13.1 km) and adolescents one lap (4.3 km) as fast as possible. No other instructions regarding pacing strategy were given. The skiers started at 2-min intervals in ranked order to minimize overtaking and possibly drafting. The asphalt was dry on all test occasions and the athletes wore tight-fitting clothes during the race. Each skier was equipped with a Catapult S5 unit, which was used for position and speed calculations, and gear classification. The TT terrain was described according to FIS’s official homologation manual, which defines different segments: A, B and C climbs (no C-climbs on this course), undulating terrain (UT) and downhills (D) (Fig. 1) (A-climb = Major uphills, partial height difference (PHD) ≥ 30 m. B-climbs = Short uphills, 10 m ≤ PHD ≤ 29 m, incline 9 - 18%. UT = combination of flat and rolling terrain including short climbs, flat sections and downhills). See the official manual for further details [116]. A trajectory through the TT course was

measured before the data collection, using a highly accurate dual-frequency differential carrier phase GNSS [117], and the different segments were defined based on the incline calculation of this trajectory. $\dot{V}O_{2dem}$ and propulsive power (P_{prop}) were calculated by combining measurements from the Catapult S5 unit with the trajectory of the course measured by the differential GNSS [1,80]. Heart rate data were collected throughout the TT with an HR monitor. Environmental temperature, air pressure, and wind data were retrieved from local weather stations (met.eklima.no, Meteorological Institute of Norway, Oslo, Norway).

4.7.2.2 Gear classification

Inertial and position data were retrieved from the Catapult S5 unit, which was mounted on the skiers during the TT. The manufacturer's software (Catapult Sprint, version 5.14; Catapult Sports), and a custom-made MATLAB application developed specifically for visual inspection of these measurements, were used in combination for gear classification. Classification was based on visual inspection of the gyroscope and accelerometer signals, in combination with the position and speed of the skier on the course. Gear classification was performed throughout the TT for the adolescents and during the first lap for the seniors. The classification was performed by an experienced XC-skiing coach familiar with the racecourse and the equipment/software used. Gears were defined as previously described, with three main gears ranging from G2 used at low speed uphill up to G4 used at high speed in mostly flat terrain [79]. Additionally, miscellaneous (misc.) is defined in this case as both skating without poles and active turning technique. Lastly, tucked position (TP) is defined as a downhill technique where the skiers are not generating propulsive force. The manual classification method was validated using recordings of two elite skiers who performed a TT around the same course with the same Catapult S5 unit mounted in the same way, with cameras mounted to detect the different gears. The gear classification of these two skiers was then visually inspected using the gyroscope and accelerometer signals, in combination with the position and speed of the skiers on the course, before being validated against the video. The intra-rater reliability for the combined micro-sensor and video classification was high (ICC = 0.95 (95% CI = 0.8-0.99).

4.7.2.3 Laboratory tests

Skiing *C* for the seniors was calculated from six different loads, each of 5 min, with varying treadmill speeds and inclinations as described in detail in Gløersen et al. (2020) [1]. For the adolescents, *C* was calculated from six different loads, each of 5 min, while measuring $\dot{V}O_2$, where speed was adjusted to correspond to a range in intensity of 60-80% of $\dot{V}O_{2peak}$. $\dot{V}O_{2peak}$ and ΣO_{2def} for the adults were calculated from a self-paced 1000 m test (TT_{1000m}, duration ~4 min) at 6° inclination using G3 [20]. $\dot{V}O_{2peak}$ was defined as the highest 60 s running average during the TT_{1000}. $\dot{V}O_{2peak}$ and ΣO_{2def} for the adolescents were calculated from the TT_{3min} using G2. This test was performed prior to the calculation of *C* on a separate day.

4.7.3 Paper IV

The laboratory test sessions in paper IV were identical to those described in papers I-II.

4.7.3.1 Feedback intervention

All groups performed the intervention at the same time of the season (September-October). The four XC-skiing clubs were randomly assigned to an intervention group or to the control group, and no club had skiers in more than one group. The number of boys and girls in each group was determined by the skiers volunteering for the study from each XC-skiing club.

4.7.3.2 Practice sessions

Each intervention practice session lasted ~30 min and was designed so the groups had the same timing, frequency and amount of practice time (3x5 min) and feedback time (2x5 min) during each session. The practice was only performed on the participants' non-dominant side. All groups used the same written cue cards to control the feedback information given and to guide the attention of the athletes to the session focus and corresponding appropriate movements. The list was designed combining findings from previous research on the G2 technique [81] with the experience of professional XC-skiing coaches (Table 2). The athletes were observed/filmed from the front in all intervention groups. In four of the training sessions, the athletes worked on specific tasks/questions, while in two of the training sessions (sessions 3 and 6) the questions were more open (Table 2). All groups practiced at low intensity, competition speed and sprints for each of the three types of sessions.

Table 2. An overview of the attentional cues/questions from each session in **paper IV**. The questions are translated from Norwegian.

Session focus	Session number	Attentional cues/questions	
Rhythm	1 and 4	Main question	What do you think about the rhythm?
		Secondary questions	• Do two poles and one ski hit the ground at the same time? • Are the movements "smooth and flowing" or are they "jagged"?
Sideways weight transfer	2 and 5	Main question	What do you think about the weight transfer from ski to ski?
		Secondary questions	• Does the upper body follow the same direction as the skis? • Do you push with both poles and skis actively?
Overall technique	3 and 6	Questions	• What is good about your technique? • What can be improved about your technique?

4.7.3.3 Groups

Dyad practice (DYAD): The skiers (10 boys, 3 girls) formed pairs and observed each other and gave feedback on two runs for each of the two feedback periods. In training sessions with uneven numbers of skiers, one group of three skiers worked together, with two observers to each practicing skier. The observer(s) gave feedback to the practicing athlete immediately after each run, based on the cue cards. The skiers receiving the feedback were encouraged to ask questions and discuss the feedback. The partners were the same throughout each session but changed between sessions.

Video feedback (VIDEO): The skiers (5 boys, 10 girls) formed pairs and filmed each other with their own smartphones for two runs each of the two feedback periods. In training sessions with uneven number of skiers, a group of three skiers worked together. The rest of the feedback period was used to evaluate the videos of themselves using the cue cards before they practiced based on the cues they got from studying the video. No other instruction was given to the participants.

Coaching feedback (COACH): The skiers (7 boys, 6 girls) were separated into three smaller groups, each trained by an experienced XC-skiing coach (all with 10+ years of experience). The three coaches were the same throughout the intervention. The coaches used the same attentional cue cards for feedback as the other groups. Further, the coaches gave coaching cues that were evidence-based, with an external focus of attention and autonomy-supportive instructional language to facilitate learning [118,119]. The athletes followed a rotational system such that none of the groups were the same for more than one training session and the athletes were coached by the same coach twice during the intervention. Further, before each practice session the coaches agreed on the feedback information given for each of the attentional cues and for the different variations of technical execution that could occur. The participants received feedback after two runs in each of the two feedback periods. The participants knew the focus of the session cue cards, and they were always asked their own opinion regarding their technical execution in relation to the attentional cues/questions before receiving feedback from the coach.

Control group (CON): The skiers (5 boys, 8 girls) did not attend any intervention practice session but continued with their normal training regime. They were not instructed or given any information with respect to whether they should practice the non-dominant side or not. They followed the same test procedures with the same time period between tests as the intervention groups.

4.7.3.4 Specific questionnaire for paper IV

After the post-intervention tests, the intervention groups self-reported on three items, while the control group answered only the last two of these items. Items one and two were reported on a 5-point Likert scale. The third question was a self-report on how many times they had practiced on their non-dominant side on their own during the intervention period (Table 3).

Table 3. Questionnaire the athletes answered after post-intervention testing in **paper IV**. The questions are translated from Norwegian

Item 1	**How much did you like the intervention feedback method?**				
	Very unsatisfied	Unsatisfied	Neutral	Satisfied	Very satisfied
Item 2	**Have you improved your technique on your non-dominant side?**				
	Very unlikely	Unlikely	Neutral	Likely	Very Likely
Item 3	**How many times have you trained on the non-dominant side on your own during the intervention?**				

4.8 Calculations

P_{prop} on the treadmill was calculated as the sum of power against gravity (P_g) and power against rolling resistance (P_{rr}) as previously described [9]. GE was calculated as the work rate divided by the metabolic rate under steady state condition and ΣO_{2def} was calculated as the difference between accumulated oxygen demand and accumulated oxygen consumption over the complete TT_{3min} or the TT_{1000m} for seniors in **paper III** [9,120]. The reliability coefficient (typical error expressed as CV) for the TT_{1000m} and TT_{3min} has been shown to be 2.5 and 2.4%, respectively. P_{max} in **paper II** was determined as: Work rate last step completed + (Increase in work rate each step/time each step) x finished time final step.

4.8.1 Specific calculations for paper III

During the outdoor TT, P_{prop} was calculated for sections of the course where the skiers continuously generated active propulsion. Sections with calculated P_{prop} are categorized under the same name as the segment name (Fig. 12 – green area). P_{prop} was not calculated where athletes used the tucked position (Fig. 12 – light grey area). This calculation also accounted for air drag [2] and changes in kinetic energy [80]. Specifically, the following equation was used to calculate P_{prop} (Equation 1):

$$P_{\text{prop}} = \frac{(\Delta \mathrm{E}_{\text{mech}} + \mathrm{W}_{\text{env}})}{t} = \frac{\left(m\left(\frac{1}{2}(v_{out}^2 - v_{in}^2) + g\Delta z\right) + d\left(\frac{1}{2}\rho C_D A\overline{v^2} \; + \; C_{rr} mg\,\overline{\cos\theta}\right)\right)}{t}$$

In equation 1, *m* is the mass of the athlete and equipment; v_{in} and v_{out} are the skiing speeds at the entry and exit of each segment, respectively; g=9.81 $m \cdot s^{-2}$ is the acceleration due to gravity; Δz is the change in vertical position during the segment; *d* is the length of the segment; ρ is the air's density; C_DA is the drag area of the skier, C_{rr} is the coefficient of rolling resistance; and θ is the segment's incline. Overlines indicate the average value for each segment.

4.9 Kinematic measures and questionnaires

During the treadmill roller skiing, kinematic measures were taken between 60-100 s for each submaximal work bout and during the incremental speed test in the main test session (Fig. 5). These measures are not included in this thesis, but somewhat affected the methodological choices in the laboratory. Furthermore, between the treadmill testing and the strength tests all skiers filled out a questionnaire, in which they answered questions about their thoughts on technical skills (conceptions of ability and self-regulation), self-reported their training volume and answered questions regarding their dominant and non-dominant side. Only questions about training are included in this thesis. The questionnaires were in Norwegian and can be found in Appendix 4.

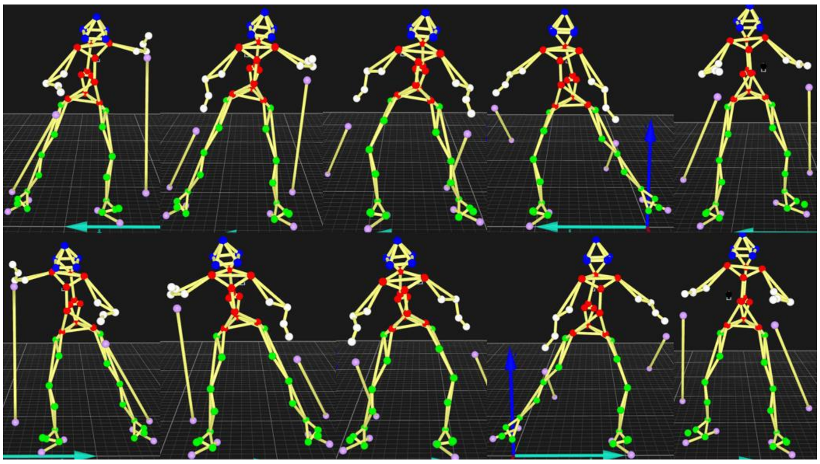


Figure 8. Illustration of the G2 technique taken from a participant during the kinematical measures. The viewpoint is directly in front of the skier. Upper panel) The skier's strong side to the left. Bottom) The skier's strong side to the right.

4.10 Statistics

Normality of the data was assessed using the Shapiro-Wilks test (α=0.05) and visual inspection of Q-Q plots. Raw data are presented as mean ± standard deviation (SD). Figures in **paper I**, relative sex differences in **paper II** and relative differences between pre- and post-intervention tests and relative differences between the non-dominant and dominant side in **paper IV** are presented as mean ± 95% confidence interval (CI). For statistical tests, a level of $P \leq .05$ was considered significant, and $P \leq .10$ was considered a tendency. Outliers in **paper IV** were assessed by inspection of boxplots and by examination of studentized residuals for values greater than ±3 (one athlete was removed from the speed test on the dominant side in VIDEO with a value of -3.27). In calculations of percent differences, the female XC skiers in **paper II** and the adolescent skiers in **paper III** were treated as the reference data (100%).

Two-tailed independent samples Student's *t*-tests were used to compare within age-group sex differences in **paper II**, between-group differences for mean TT speed, mean TT $\dot{V}O_{2dem}$ and mean regression coefficients in **paper III** and changes in W_{max} and $\dot{V}O_2$ from the submaximal workload from pre- to post-intervention in **paper IV**.

A one-way ANOVA was conducted to investigate the relative sex differences between age-groups in **paper II**, differences in time using the different gears **paper III** and on item 3 in **paper IV**. A univariate ANOVA was conducted separately on each segment to detect between-group differences in **paper III**. Further, one-way repeated measures ANOVA tests were conducted to determine whether there were statistical differences in speed, $\dot{V}O_{2dem}$, and P_{prop} between segments on laps 1-3 for the senior skiers in **paper III**. To detect differences between groups during the intervention in **paper IV**, one-way ANCOVA was run on the change scores (Post-Pre) on P_{max} from the incremental speed test and $\dot{V}O_2$ and heart rate during the submaximal workloads, to control for pre-intervention scores. A two-way ANOVA was conducted on group difference for different gear selections for speed and incline (2 x 5 design) and two-factor mixed ANOVAs were conducted to determine whether there were statistically significant between-group differences for speed (2x20 design), and for $\dot{V}O_{2dem}$ and P_{prop} (2x13 design) for the different segments throughout the TT in **paper III**.

Partial eta squared effect sizes (η_p^2) were reported for ANOVA and ANCOVA tests in **papers III** and **IV** where 0.14 or more, 0.06 or more and 0.01 or more were considered large, medium and small effects, respectively [121]. Bonferroni corrections for multiple comparisons were applied for all ANCOVA and ANOVA tests in **paper III** and **IV**. Pearson's product moment correlations were applied for correlations. Correlation coefficients were 0.1 to 0.3 small, 0.3 to 0.5 moderate, 0.5 to 0.7 large, 0.7 to 0.9 very large and >0.9 extremely large. The magnitude of differences between variables was expressed as standardized mean differences (Cohen's *d* effect size; ES). The criteria to interpret the magnitude of the ES were as follows: trivial 0.0–0.2; small 0.2–0.6; moderate 0.6–1.2; large 1.2–2.0; and very large >2.0 [122]. Stepwise multiple regression analyses were run in **paper I** with $\dot{V}O_{2peak}$, ΣO_{2def} and GE as independent variables to explain TT_{3min},
distance and sprint performance, separately. Boys and girls were analyzed separately.

The pacing pattern in **paper III** was considered variable if there were statistically significant changes in relative P_{prop} between segments. In **paper III**, Mauchly's test was used to test the assumption of sphericity. As the value of epsilon was less than 0.75 when the sphericity assumption was violated, *P* - values were adjusted according to Greenhouse-Geisser. The typical error (expressed as CV%) for the incremental speed test was 2.7% (calculated from the familiarization test and the pre-intervention test). We were not able to calculate the typical error for $\dot{V}O_2$ during the submaximal workload for the adolescent skiers, but the typical error for elite athletes is 1.2% [36].

In **paper IV** a Kruskal-Wallis H test was run to determine whether differences were present between groups for items one and two in the questionnaire (Table 3). Distributions of each item were assessed by visual inspection of a boxplot. Distributions for the items were not similar between groups. Therefore, we compared mean ranks. Pairwise comparisons were performed using Dunn's (1964) procedures with a Bonferroni correction for multiple comparisons [123]. Adjusted *P* - values are presented and values in parentheses are mean ranks. Statistical analyses were performed using SPSS statistical package version 24 (SPSS Inc. Chicago, IL) in all papers. Graphpad Prizm 8 and 9 (GraphPad Software, San Diego, CA) were used in **paper I-II** and **IV**. SigmaPlot 14.0 (Systat Software, Inc., San Jose, CA) was used in **paper III**.

5 Results and discussion

In this chapter, the main findings from the four studies are presented and discussed. Detailed results for each specific study are presented in the manuscripts at the end of this thesis.

This research project used a combination of laboratory tests with in-field experimental approaches to explore the determinants of XC skiing performance in male and female adolescent competitive XC skiers. We also used a novel approach with an applied perspective and a long-duration technique training intervention to increase individual technique feedback and thereby potentially improve technique training.

There is a substantial body of research in the field of XC skiing regarding the demands and determinants of performance in junior and senior skiers, but less is known for adolescent skiers. As there is anthropometric, physiological, and biomechanical differences between adolescent and senior skiers the knowledge of the determinants of XC skiing performance in senior skiers cannot simply be scaled down and applied to adolescent athletes.

Thus, this thesis aimed to provide new information about the determinants of performance and technique learning in applied settings in male and female adolescent XC skiers.

5.1 Determinants of performance

5.1.1 Physiological determinants

$\dot{V}O_{2peak}$ relative to body weight was highly related to both laboratory (Fig. 9) and on-snow distance performance (Fig. 10), while upper-body strength and BMI contributed most to sprint performance in both sexes (Fig. 11). These characteristics are similar to those previously found in senior skiers [11,28]. However, the strong relationship between sprint (duration of ~2.5-3 min) and distance performance (duration of ~12-20 min) indicates that there is an overlap in determinants of performance for adolescent skiers in these two disciplines. $\dot{V}O_{2peak}$ relative to body weight was the only determinant that contributed substantially to all three performance settings in the present thesis (Appendix 2, Table 8). Thus, in line with results from adult skiers [10,11], $\dot{V}O_{2peak}$ is a key physiological determinant of overall adolescent skiing performance.

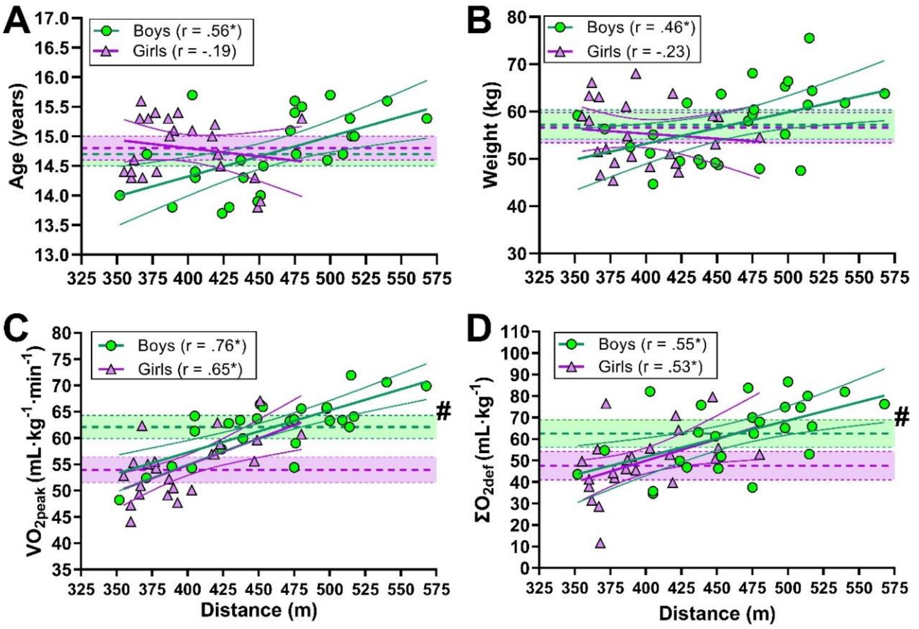


Figure 9. The most important determinants of TT_{3min} performance. A) age, B) Body weight, C) $\dot{V}O_{2peak}$ relative to body weight and D) ΣO_{2def} relative to body weight. Green circles represent individual values for the boys and purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green area for the boys and purple for the girls). Thick and narrow lines represent the best fit regression line and the 95% confidence bands respectively (green lines for the boys and purple for the girls). * Correlation is significant at the .05 level. # significant difference between boys and girls. $\dot{V}O_{2peak}$ = maximal ski-specific oxygen uptake, ΣO_{2def} = accumulated oxygen deficit.

Increased $\dot{V}O_{2peak}$ is related to increased muscle mass in adolescent skiers [31], which is further related to maturity status [46]. As seen in Fig. 9B, increased body weight in these adolescent boys is positive for TT_{3min} performance. Increased weight for these well-trained boys is most likely a large proportion muscle mass, and the weight may thereby also affect the $\dot{V}O_{2peak}$.

A large training volume during adolescence has previously been related to a high $\dot{V}O_{2peak}$ [30] and increased performance [31]. However, more specific endurance training during adolescence does not necessary produce a higher $\dot{V}O_{2peak}$ compared with similar volumes of training mainly aimed at developing motor skills [31]. In the present thesis, the self-reported total training hours for the boys, but not girls, had a large to very large correlation for the three performance settings (TT_{3min}; r = .81, Sprint; r = -.53, Distance; r = -.56) and a large correlation with $\dot{V}O_{2peak}$ relative to body weight (r = .56). Hence, higher training volumes with a focus on developing fundamental and sport-specific motor skills [31] should be considered as a major part of the training program in adolescent (male) skiers for improving performance.

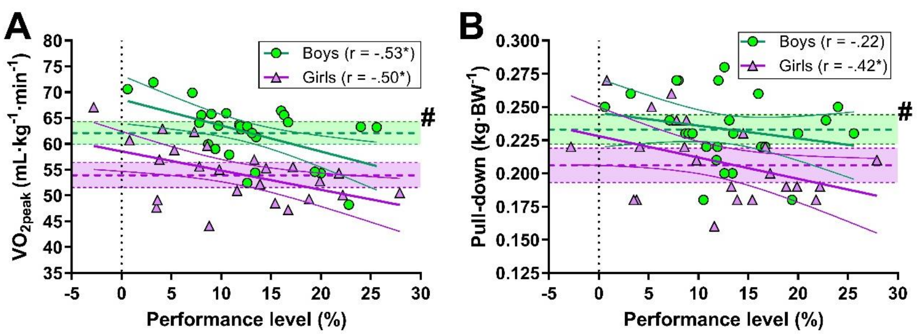


Figure 10. The most important determinants of distance performance. A) $\dot{V}O_{2peak}$ and B) Pull-down strength Green circles represent individual values for the boys and purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green area for the boys and purple for the girls). Thick and narrow lines represent the best fit regression line and the 95% confidence bands respectively (green lines for the boys and purple for the girls). * Correlation is significant at the .05 level. # significant difference between boys and girls. $\dot{V}O_{2peak}$ = maximal ski-specific oxygen uptake, ΣO_{2def} = accumulated oxygen deficit, BW = body weight.

Upper-body strength and BMI contributed most to sprint performance in both sexes in the present thesis (Fig. 11). Higher muscle mass, and thereby strength, have also been found in senior sprint skiers compared to performance-matched distance skiers [11]. It therefore seems that similar differences as in senior skiers in physiological demands between sprint and distance performance also exist in adolescent skiers. Upper-body power has also previously been observed as a determinant of XC skiing performance in both senior [28] and adolescent [48] skiers. In senior skiers, this is probably related to the close relationship between muscle mass and anaerobic capacity [9,42].

The large correlation found between ΣO_{2def} and TT_{3min} performance in **paper I** was not present in on-snow performance. Anaerobic capacity per se may not reflect skiing performance, but rather the ability to repeatedly use and recover the energy reserves represented by the oxygen deficits [1]. As skiers repeatedly attain substantial oxygen deficits in individual uphills [1], anaerobic energy turnover and subsequent recovery from these anaerobic bursts seem as an important piece of the performance puzzle for XC-skiing.

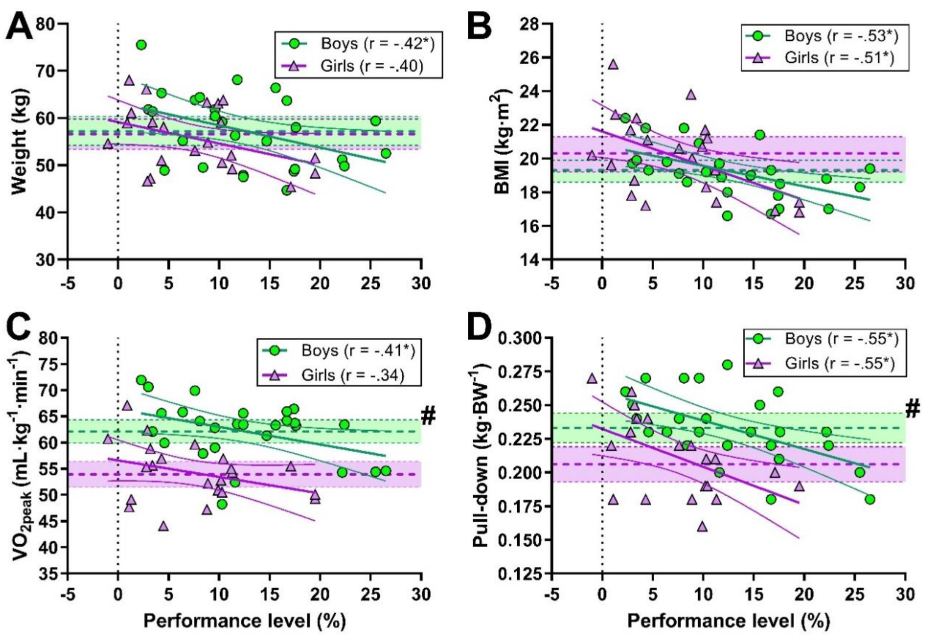


Figure 11. The most important determinants of sprint performance. A) Body weight, B) BMI, C) $\dot{V}O_{2peak}$ and D) maximal pull-down strength. Green circles represent individual values for the boys and purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green area for the boys and purple for the girls). Thick and narrow lines represent the best fit regression line and the 95% confidence bands respectively (green lines for the boys and purple for the girls). * Correlation is significant at the .05 level. # significant difference between boys and girls. $\dot{V}O_{2peak}$ = maximal ski-specific oxygen uptake, BMI = body mass index, BW = body weight.

5.1.2 Exercise intensity and pacing pattern

Adolescents' ability to repeatedly use and recover their energy reserves seems to be similar to that observed in senior skiers, with a tendency for higher mean exercise intensity during the race than the senior skiers (120 ± 14 and 112 ± 10% of $\dot{V}O_{2peak}$, adolescents and seniors respectively, P = .089, η_p^2 = .160). The adolescent skiers in **paper III** showed a highly variable metabolic energy requirement over the course, with $\dot{V}O_{2dem}$ exceeding the maximal aerobic power in the uphills and $\dot{V}O_{2dem}$ around and below maximal aerobic power in flatter terrain (Fig. 12, upper panel), corresponding to findings for adult XC-skiers in previous studies [1,2,8]. The difference between the adolescents and seniors for VO_{2peak} and ΣO_{2def} relative to body mass was ~20-25% and in line with previous findings [75,76]. Therefore, the similar relative $\dot{V}O_{2dem}$ for uphills between the adolescents and seniors indicates that adolescents use the same relative fraction of their anaerobic capacity as senior skiers. The relative anaerobic contribution (estimated using the ΣO_{2def}) to total energy requirements during TT_{3min} was also similar in the adolescents and seniors.

Estimating the exercise intensities and energy demands during XC ski racing have been revitalized from the original work by Norman et al. (1987; 1989) [101,124] the recent years [1,2,8,126] (Table. 4). These studies clearly show that an important attribute of XC skiers is to repeatedly attain and recover from exercise intensities above their $\dot{V}O_{2peak}$. Interestingly, the exercise intensity of sprint and distance skiing appear to be relatively similar, although the race duration is substantially different (Sprint; ~2-4 min, Distance; Senior male >30 min Senior female >20 min, Adolescents >12 min). Furthermore, the topography of the course play a major role in the pacing in different segments of the racecourse as the length and inclination of a segment affect exercise intensity [2]. The exercise intensity is also affected by the length and inclination of the previous segment. Learning to properly analyze and visualize the racecourse could therefore be a good strategy for improved pacing and, thereby, performance for adolescent skiers. However, how these findings of intermittent exercise intensity can be transformed to better training strategies is important for future studies.

Table 4. An overview of different studies exploring estimated exercise intensity (expressed as relative oxygen demand, $\dot{V}O_{2dem}$) during rollerski and on-snow traditional XC ski racing of different length. The studies have used different methods and estimations and the $\dot{V}O_{2dem}$ can therefore not be directly compared between studies. Studies using other estimations than $\dot{V}O_{2dem}$ for exercise intensity are not represented in the table.

	Study	Group	Dist.	Technique	Incline (°)	$\dot{V}O_{2dem}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	$\dot{V}O_{2dem}$ (% of $\dot{V}O_{2peak}$)
Distance	Norman & Komi, 1987 [124]	SM	15 km	CL, DIA	9	154	---
	Norman et al., 1989 [101]	SM	30 km	CL, DIA	11.8	83	---
	Karlsson et al. 2018 [2]	SM	13.5 km	SK	Uphills	78 - 116	110-160
				SK	Flat	~73	~100
	Gløersen et al. 2020 [1] and **Paper III** (Sollie et al. 2020 [125])*	SM	13.1 km	SK	Uphills	79-123 (avg. 100)	102-160 (avg. 129)
					Undulating	50-103 (avg. 72)	64-134 (avg. 93)
		AM	4.5 km	SK	Uphills	67-100 (avg. 86)	105-157 (avg. 134)
					Undulating	51-109 (avg. 66)	79-169 (avg. 104)
Sprint	Sandbakk et al., 2011 [13]	SM	1.8 km	SK, G3	3.4	112	160
	Andersson et al. 2017 [126]	SM	1.3 km	CL, DIA	7	75-78	115-20
				CL, DP	1	59-62	90-95
	Andersson et al. (2019) [8]	SM	1.6 km	SK, G3 and G2	3.7 and 4.2	95 and 91	132 and 126
				SK, G3	0.3 (end-spurt)	111	154
		SF	1.6 km	SK, G3 and G2	3.7 and 4.2	77 and 74	131 and 127
				SK, G3	0.3 (end-spurt)	90	152

SM = senior male; AM = adolescent male from **paper III** (marked yellow); SF = senior female; CL = classic; SK = skate; DIA = diagonal; G3 = Gear 3; G2 = Gears 2; Dist. = race distance *The senior skier in Gløersen et al. (2020) is the same skiers as the senior skiers in Sollie et al. (2021).

The complexity of on-snow skiing is demonstrated in the present thesis, as $\dot{V}O_{2peak}$, ΣO_{2def} and GE explained ~80% of the TT_{3min} performance, but only a small part of the variation in on-snow sprint and distance performance (~20-30%) in **paper I** (Appendix 2, Table 8). A part of the complex performance puzzle for outdoor skiing is the pacing during a race. The adolescent skiers demonstrated a higher effort during the initial phases of the outdoor roller ski race with higher relative $\dot{V}O_{2dem}$ compared to the senior skiers ($P < .05$ for U1, B1, B2 and *P* = 0.10 for U2) in **paper III**, and thereby a more pronounced positive pacing, while there was no difference between groups for the remaining segments (Fig. 12, upper panel). There was no difference in speed between groups for the five first segments which corresponded to 110% and 94% of the mean speed for the whole TT, for the adolescents and seniors respectively. Given the lower physiological capacity in the adolescent skiers compared to the senior skiers, this further imply a positive pacing for the adolescents compared to the seniors.

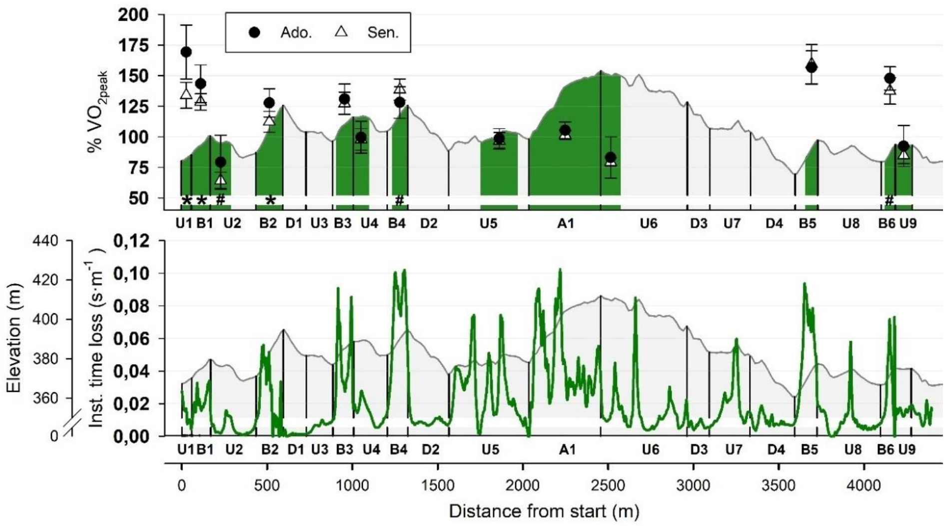


Figure 12. Calculations of relative oxygen demand and instantaneous time loss for the adolescents compared to the seniors throughout the TT in **paper III**. Upper panel) Segment oxygen demand (VO_{2dem}) (% $\dot{V}O_{2peak}$). Lower panel) Instantaneous time loss (Seconds per meter) for the adolescents compared to the seniors throughout the TT (green line). Data are presented as mean ± SD. *significant between-group differences (*P* < .05). # tendency for between-group differences (*P* < .10). The altitude profile of the racetrack used during the TT is shown behind the data points and is the same in both panels. Segments are separated by drop lines. The green area indicates the section of each segment where the athletes skied continuously without using TP and where measurements of VO_{2dem} were calculated. The calculations for the seniors are averaged for the three laps.

For long duration endurance sports, such as distance XC-skiing, an even pacing strategy seems the best choice [5,31]. Elite male XC-skiers have a more even lap-to-lap pacing compared to their slower counterparts [62,71] and older and more experienced skiers seem to adopt a more even pacing than their younger counterparts of similar performance level [72,73,127]. Moreover, learning to optimize pacing is an important factor in the performance development of young athletes [66,68], which implies that adolescent skiers could benefit from adopting a more conservative pacing to enhance their performance (Losnegard et al.,2021, ahead of print)

The adolescents were slower than the seniors in all types of terrain inclinations (mean differences in speed of 13 ± 8%), with a hierarchy in differences for uphills (19 ± 10%), undulating terrain (11 ± 5%) and downhills (8 ± 4%) (all, $P < .05$), similar to the difference between male and female elite XC-skiers during a race with similar relative exercise intensity [8]. This is illustrated in Fig. 12 (lower panel) where instantaneous time loss ($s \cdot m^{-1}$) for the adolescents compared to the seniors increased when inclination increased. Uphill performance is a major determinant of overall performance in XC-skiing and it was therefore expected that the largest speed difference would be in the uphills [1,3]. However, although the speed difference between groups for uphills (~19%) was larger than for undulating terrain (~11%), the corresponding difference for P_{prop} was similar in both terrains (~16% and ~17%, respectively). Hence, the difference in speed was smaller between groups for undulating terrain than for uphills with similar differences in P_{prop}, as previously found between male and female elite skiers [8]. At high speeds on undulating terrain, a larger part of the P_{prop} is used to overcome air resistance compared to uphills because of the quadratic increase in air resistance with increasing speed. However, how to most effectively pace oneself in different segments and terrain on the racecourse in relation to each other is not fully understood and is an important aspect for further studies.

5.1.3 Technique characteristics

The lower speed during the uphills in the adolescent skiers compared to the senior skiers affected gear selection, meaning that the adolescents used more G2 and less G3 than the seniors during the outdoor TT (Fig. 13). When analyzing all the skiers in **paper III** together, the use of G3 was correlated to faster finishing times (r = -0.85), suggesting that speed is the major factor in gear selection as previously observed [3,4,8,34,71,128].

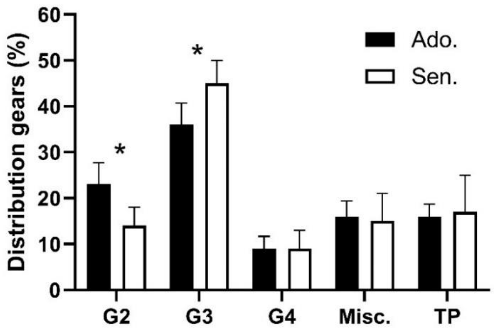


Figure 13. Distribution of gears as a percentage of total lap time for the first lap for the adolescents and seniors. Data are presented as mean ± SD. * significantly different between groups (P < .01). G2, G3, G4, Misc., and TP is the different sub-techniques used. See 1.2 Explanation for further details.

Both the adolescents and seniors used the different gears within the normal speed ranges as proposed by Losnegard (Fig. 2) [18]. However, a novel finding in **paper III** is the significant difference in speed between the adolescents and seniors for gear selections, where the adolescents used G4 ($P < 0.001$, $\eta_p^2 = 0.15$), Misc. ($P < 0.001$, $\eta_p^2 = 0.14$), and TP ($P < 0.001$, $\eta_p^2 = .16$) at lower speeds than the seniors, also showing a tendency for lower speed for G3 (P = 0.10, $\eta_p^2 = .31$). Furthermore, the adolescents used the G4 at a greater incline compared to the seniors ($P = .007$, $\eta_p^2 = .08$) (Fig. 14).

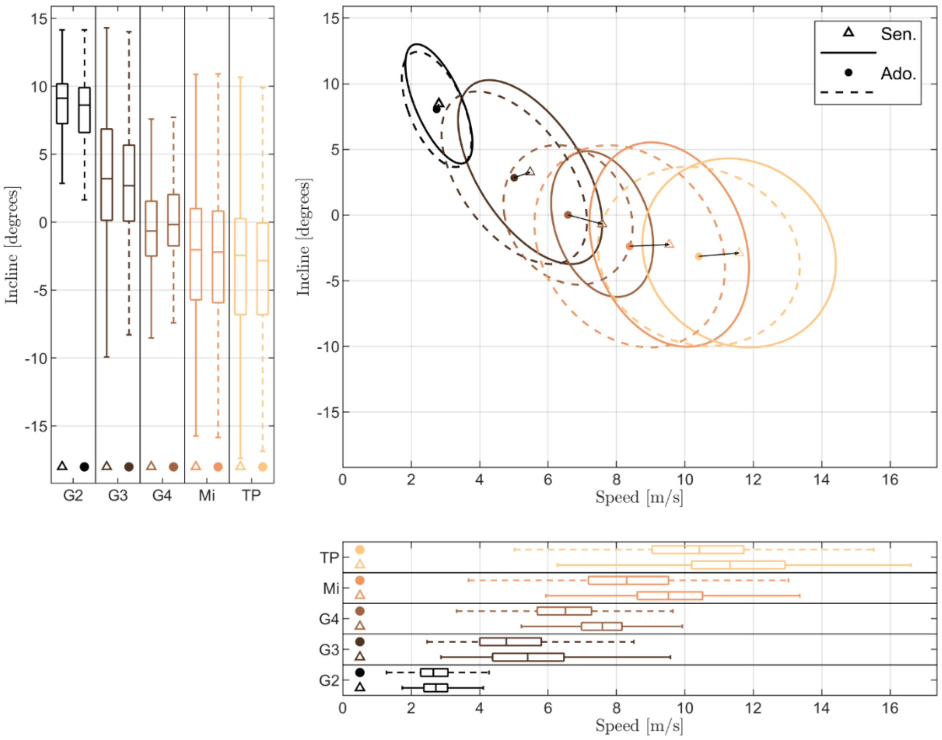


Figure 14. Gear selection during the TT for the adolescents (Ado.) and seniors (Sen.). Dotted ellipses represent the adolescents, while solid ellipses represent the seniors. One ellipse represents 1SD (68%) of the measurement for that particular gear and group. The arrows represent the shift of mean speed and incline for the different gears for the adolescents compared to the same mean for the seniors. On each boxplot, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers. An outlier is a value that is more than 1.5 times the interquartile range away from the top or bottom of the box.

This indicates that there could be indirect factors that influence gear selection, other than speed. With increasing speed, the time window for the propulsion phase decreases and limits the possibility to generate force [79]. G3 relies more on propulsion forces from the upper body compared to G2 [129] and the force exerted through the poles relative to body weight may be a potential trigger signal for gear transition [128]. Since the contribution from the upper body is an important performance characteristic for high-speed gears [15] and poling forces are estimated to cost as much as 40 times more than ski force generation [129], combined with the assumption of better upper body strength and oxidative capacity in the seniors than in the adolescents, this may have affected the different speeds observed for these “high-speed gears” between the adolescents and seniors in the present study.

5.2 Sex difference

This thesis shows that the sex difference in performance and physiological determinants of performance found in world-class skiers is already apparent, with a similar magnitude, in adolescent skiers of 14-15 years of age and in junior skiers (Fig. 15). The sex difference in TT_{3min} performance for the adolescent skiers was 18% (P <0.01, ES = large, 1.48) when all adolescent skiers were analyzed (**paper I**) and 23% (P < 0.01, ES = very large, 2.76) when the best adolescent skiers were analyzed (**paper II**). The corresponding sex difference for P_{max} was 10% (P < 0.01, ES = large, 1.20) and 15% (P < .01, *ES* = very large, 2.67) respectively. The sex difference in performance thus increased by 5% when comparing the best adolescent skiers, rather than all the skiers. The distances achieved during TT_{3min} were 24% and 17% longer in male junior and senior skiers respectively compared to their female counterparts (P < .01, *ES* = very large, 2.67–4.18, Fig. 14) and 19% and 14% higher P_{max} respectively compared to their female counterparts (P < .01, all *ES* = very large (2.43–2.67), Fig. 15).

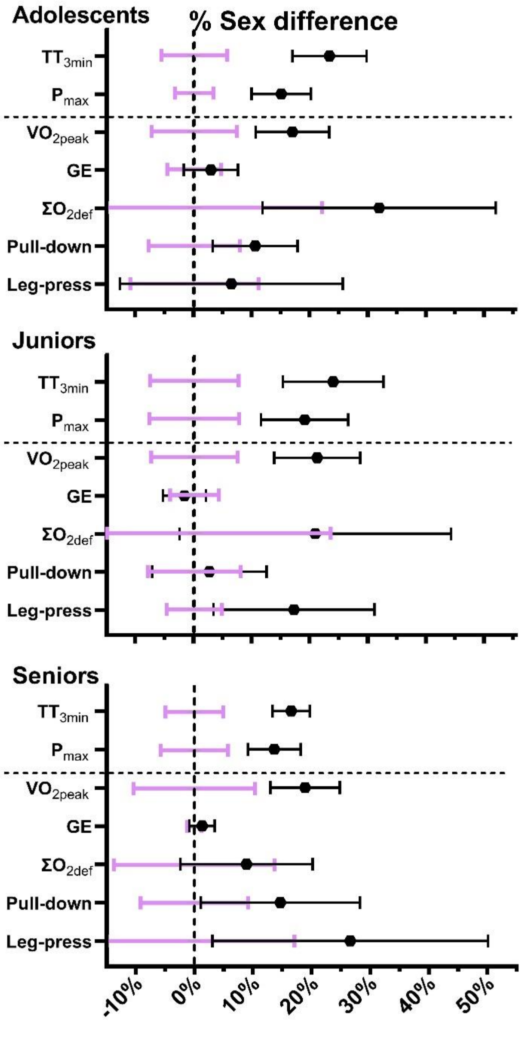


Figure 15. Visualization of the percentage difference between male and female XC skiers for roller ski performance, $\dot{V}O_{2peak}$, GE, ΣO_{2def}, pull-down and leg-press strength in the different age-groups. The black symbols and black error bars represent mean ± 95% CI for the male skiers as percentages compared to the mean of the female skiers (defined as 100%) in the same age-group (black dotted line at 0%). Purple error bars represent ± 95% CI in percentages around the mean of the female skiers. Negative error bars below -15% are cut for visualization purposes. TT_{3min} = 3-min maximal time trial, P_{max} = highest 15-s power output during the incremental speed test, ΣO_{2def} = accumulated oxygen deficit during the TT_{3min}, GE = Gross Efficiency, Pull-down = Single arm pull-down maximal strength, Leg-press = Single leg press maximal strength.

The larger sex difference in TT_{3min} performance than P_{max} can possibly be attributed to the duration of the tests and, thus, the higher aerobic energy contribution in the TT_{3min} than the P_{max} test. The P_{max} test lasted 64 ± 11 s for the adolescent girls and 85 ± 19 s for the adolescent boys. Consequently, the TT_{3min} test requires a relatively larger aerobic energy contribution compared to the P_{max} test (~70–75% vs ~45–55% [130]) and thus favors skiers with a higher $\dot{V}O_{2peak.}$.

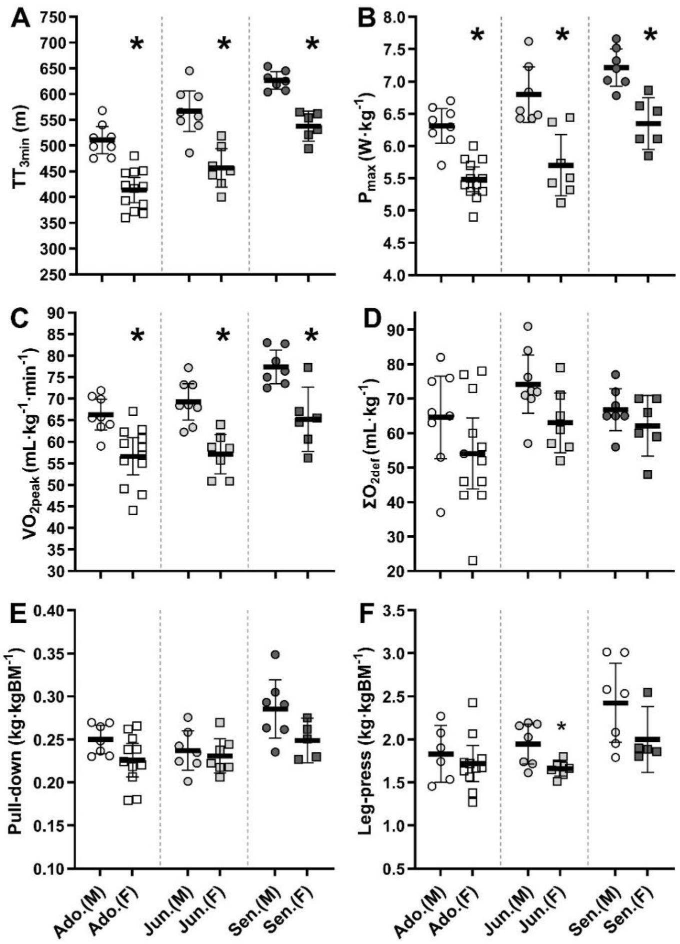


Figure 16. Measurements from the maximal tests in paper II. A) Distance covered (m) during the TT_{3min}; B) P_{max}, highest 15-s power during the incremental speed test; C) relative $\dot{V}O_{2peak}$; D) relative ΣO_{2def} from TT_{3min}; E) single-arm pull-down and F) single leg-press weight relative to body mass. Data are presented as mean ± 95% CI. * significantly lower compared to male counterparts ($P < .05$). kgBM = kg body mass, TT_{3min} = 3-min maximal time trial. Ado.; adolescent skiers, Jun.; junior skiers, Sen.; senior skiers, (M); Male, (F); Female.

In **paper I** where all the adolescents were included, the boys achieved 15% higher $\dot{V}O_{2peak}$ relative to body weight compared to the girls ($P > 0.01$, ES = large, 1.43). In **paper II**, where only the best adolescent skiers participated, the boys achieved 17% higher $\dot{V}O_{2peak}$ compared to the girls (Fig. 15-16). The junior and senior male skiers achieved a 21% and 19% higher $\dot{V}O_{2peak}$ respectively compared to their female counterparts (Fig. 15-16). The greater sex difference in performance for the TT_{3min} than the P_{max} may therefore be related to the higher $\dot{V}O_{2peak}$ in the male skiers compared to the female skiers. The sex difference in $\dot{V}O_{2peak}$ has been previously shown to be an important contributor to the sex difference in endurance performance in other endurance sports [50] and in elite senior skiers matched for performance level [60].

Previously, a similar metabolic demand relative to $\dot{V}O_{2max}$ between senior male and female skiers was found in outdoor race settings [8], showing a similar relative anaerobic contribution to total energy requirements between sexes in XC skiing, as supported by the present thesis (**papers I** and **II)** with around 40% anaerobic contribution in all age-groups. We did not find a sex difference in relative strength or ΣO_{2def} in any groups in **paper II** (Fig. 15-16)**,** but when we included more adolescent skiers in **paper I**, we found a sex difference for upper-body strength and ΣO_{2def} relative to body weight between the adolescent boys and girls, indicating a real difference that was not detected (Type 2 error) in **paper II**. Similar finding was present in the junior and senior skiers with no significant sex differences in ΣO_{2def} relative to body weight, but with a moderate to large ES (ES = 0.70 and 1.48, juniors and seniors respectively).

The adolescent boys achieved 32% greater ΣO_{2def} compared to the girls in **paper I** ($P > 0.01$, ES = moderate, 0.97) and 23% sex difference in paper **II** ($P = .15$, ES = moderate, 0.73). Although the best girls in **paper II** reduced the sex difference in ΣO_{2def}, there was no significant difference between all the girls in **paper I** and the best girls in p**aper II** in ΣO_{2def}. Lower-body maximal strength relative to body weight was similar between boys and girls both when all adolescents were analyzed together (**paper I**) and when the best skiers were analyzed separately (**paper II**). Upper-body maximal strength was 13% greater in boys compared to girls when all adolescents were analyzed together ($P < 0.01$, ES = moderate, 0.93) (**paper I**) (Fig. 10B) while a tendency toward sex difference was found in the best adolescent skiers (11% dif., $P = 0.07$, ES = moderate, 0.98) (**paper II**) (Fig. 15-16). This is similar finding as previously observed in senior skiers [131], although with a somewhat higher sex difference of 24% compared to the 11-13% sex difference in the adolescent and 15% in the senior ($P = 0.07$) skiers in the present thesis. There was further a tendency ($P = 0.08$) that the best adolescent girls in **paper II** had greater upper-body strength compared to all the girls in **paper I.** There is however uncertain how these results should be applied for skiers, and the results from this thesis corresponds with previous studies observing that strength and strength training to be a complex attribute in XC skiing. This may, however, imply that individual considerations should be done.

Finally, as previously found in senior skiers, we did not find any sex difference in GE for any of the age-groups in the present thesis [59,60].

5.2.1 Maturity

We included no maturity measures in this research project, but increased weight in the well-trained boys participating in this project most likely relates to increased growth-related muscle-mass, which is an explanatory variable associated with maturity status [46]. It seemed that age and weight were more important for laboratory performance in the boys than in the girls in **paper I**. When ranking the skiers based on TT_{3min} performance and comparing the top and bottom-ranked tertile in the boys in **paper I**, the top-performing tertile were significantly older, heavier and taller compared to the bottom-performing tertile (see appendix 1). The boys who also participated in **paper II (**the eight best boys), were also heavier than the mean of all the boys in **paper I**. This was not apparent in the girls, and unlike the boys, the top-performing tertile in the girls was lighter than the bottom-performing tertile. This shows that boys born early in the year (relative age effect) and maturing early (i.e. greater muscle mass) had a performance advantage compared to those who were born and matured later. The relative age effect has also been previously shown in adolescent winter sport athletes [54,55] and maturity status has previously been found to be a major confounding variable for performance in male adolescent skiers [48] with an estimated peak height velocity (PHV) between 13.8 [31] and 14.2 years [48]. Although this is ~5-9 months younger than the adolescent boys participating in this research project, it may indicate that some of the boys in this research project were in the period around PHV. Girls mature earlier than boys, and the PHV for female adolescent skiers is estimated to be ~12.2 years [31,48]. Most of the adolescent girls participating in this project were thereby likely past PHV, and the top- and bottom-performing tertile were more similar in age and anthropometrics than the boys. Regardless, anthropometric variables do not seem to predict future success [29,39] and should thus not be an area of focus during adolescence.

5.3 Technique training

When timing, frequency and amount of feedback are similar, coaching feedback from a competent coach seems superior in terms of combined performance, perceived enjoyment, self-perception of improved technique and amount of self-practice performed compared to video feedback and dyad practice. This may imply that coaches can satisfy fundamental psychological needs found to be important, such as enhanced expectancies and positive affect, which may influence learning and performance outcomes in athletes [119]. Further, the greater amount of self-practice in the coaching group may reflect intrinsically regulated motivation for practice [119], which has been found to positively influence performance in the long run [132]. In the present thesis, each coach only coached five skiers per session. Therefore, having a low athlete-to-coach ratio in applied group practice settings is a good approach for technique training, if possible. However, applied youth sport practice settings usually do not have this luxury and furthermore, the coaches may be non-professionals.

Table 5. Differences for P_{max} during the incremental speed test from pre- to post-intervention testing on dominant and non-dominant side.

	Dominant side		**Non-dominant side**	
	P	**Cohens *d***	***P***	**Cohens *d***
Dyad	0.37	.26, small effect	0.74	.09, very small effect
Video	0.97	.01, very small effect	0.03	.65, medium effect
Coach	0.31	.29, small effect	< 0.01	.89, large effect
Control	0.79	.08, very small effect	0.08	.54, medium effect

Feedback methods need to facilitate beneficial technique modification to have relevance for the skiers. Of the two observational feedback methods, only the video group improved P_{max} during the intervention (2.1 ± 1.8%, Table 5). The video group received no coaching feedback, but achieved similar changes in performance as the coaching group (3.8 ± 2.4%, Table 5). The effect of video feedback on technique improvements has been equivocal [87], but in the present study the attentional cue cards may have helped the athletes to direct their attention to relevant aspects of the technique [97]. The skiers' self-observation may be a more powerful tool than observation by others because the self-generated video action is more informative to the skier due to heightened similarity [133]. Video feedback using athletes' own smart phones with attentional cue cards may therefore serve as a complementary tool for coaches providing technique feedback in large groups.

The dyad group did not improve performance (P_{max} from pre- to post-intervention: -0.2 ±1.6%, Table 5) and was the only group with lower Pmax than the coaching group *(P* = 0.05, diff. of 4.0 %, ES = 1.18, large effect) (Fig. 17, upper right panel). The observations from the practice sessions were that the skiers often focused on non-relevant movements and gave feedback with an internal focus of attention. It has been repeatedly shown that an external focus of attention facilitates learning [118] and the skiers may have adopted a higher self-focus and thus became overly aware of their movements, which may have reduced technique learning [119]. Participants in collaborative or cooperative learning situations often anecdotally report more enjoyment than they have experienced when learning alone [134]. However, this was not expressed in the present study, where the dyad group ranked low on enjoyment. Many of the skiers commented that they thought it was difficult to coach other athletes even though they had the attentional cue cards. The video group did not express this view when “coaching” themselves. The skiers’ preexisting knowledge of the movement was perhaps too limited to understand how to best instruct other skiers [132] and dyad practice may be a method better suited to more experienced athletes with higher sport-specific technique content knowledge.

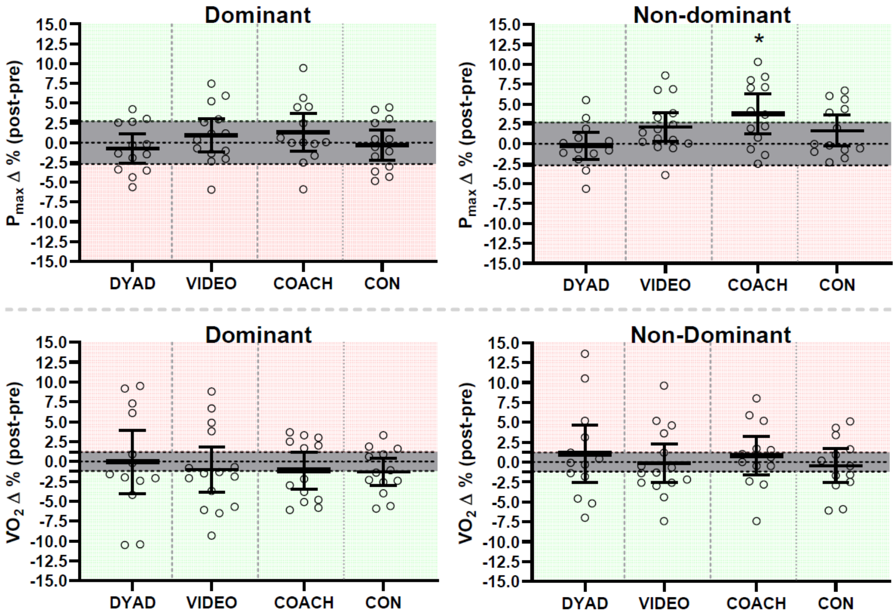


Figure 17. Upper panel: Percentage change score from pre- to post-intervention for the speed test. There was a tendency to a difference in change scores for the non-dominant side between interventions (upper right panel) (P = .07, η_p^2 = .134), with a significant difference between COACH and DYAD (P = 0.05, diff. of 4.0 %, *ES* = large effect, 1.18). No difference was found between any of the groups for the dominant side (Upper left panel, P = 0.61, η_p^2 = .036). Grey area indicates the typical error of the test expressed as CV of 2.7%. Lower panel: Percentage change score from pre- to post-intervention for $\dot{V}O_2$ on dominant and non-dominant side during sub-maximal skiing. Grey area indicates the typical error of the test expressed as CV of 1.2% for adult athletes. Mean ± 95% CI. * significantly different from non-dominant side in DYAD controlled for pre-intervention scores. Circles represents individual percentage change scores. The green area indicates enhanced performance during intervention while the red area indicates decreased performance.

No change was found in skiing economy in any of the groups from the pre- to post-intervention submaximal efforts (Fig. 17, bottom panels). Our 5-week intervention period with 6 x 30 min training sessions may have been too short with too little volume of technical training, as changing skiing economy with technique modifications may take longer to develop in adolescent skiers [29,45]. Further, exercise intensity is an important factor in terms of how skiers cope with the G2 non-dominant technique in cross-country skiing, which skiers find more challenging at higher intensities [135]. This was also evident in the present study as the magnitude of the difference between the dominant and the non-dominant side increased as the speed increased (Appendix 3, Table 9) and "high-speed performance" improved, but not skiing economy at lower speeds.

5.4 Methodological considerations

5.4.1 $\dot{V}O_2$ measures

The testing in this research project was conducted over two years due to the time-consuming methods involved. In **paper I**, 27 adolescent skiers were tested in 2017, while the remaining skiers were tested in 2018. In **paper II**, 4 male and 7 female adolescent skiers and 3 male and 2 female junior skiers were tested in 2017, while the remaining participants were tested in 2018. Breath-by-breath measures were chosen in 2017 based on feedback from adolescent participants during a pilot study and methodological consideration regarding kinematical measures. As a difference between breath-by-breath and mixing chamber measures was found after the first round of testing in 2017 [1], and world-class skiers were going to be tested in 2018, we changed to averaged measures (mixing chamber). The number of skiers tested by breath-by-breath and mixing chamber measures in **paper I** was balanced in both boys and girls and in **paper II** we do not make comparisons between age-groups. This should therefore not affect any conclusions reached in this thesis.

In **paper III**, breath-by-breath measures were used for the seniors, while averaged measures (mixing chamber) were used for the adolescents. For the purposes of Gløersen's (2020) study, instantaneous measurement of $\dot{V}O_2$ was a key point [1]. Since instantaneous measurements were not needed for the adolescents, we chose to measure $\dot{V}O_2$ with a mixing chamber, which has been thoroughly validated [136]. However, as relative $\dot{V}O_{2dem}$ is used in **paper III** to compare groups, this should not affect the results. A detailed description of the validation of the breath-by-breath measures can be found in Gløersen et al. (2020), supplemental content 1 [1].

5.4.2 Maturation measures

Due to the time-consuming methods and an original focus on kinematical measures we did not conduct any maturation measures in this thesis. As the main purpose of the papers in this thesis was not to assess the effect of maturation on the determinants of performance in adolescent skiers, the study designs were deemed adequate for this particular group.

5.4.3 Special consideration in the papers

5.4.3.1 Paper I

For on-snow performance, we only assessed two races in each racing format (sprint and distance) for each skier. We then eliminated the worst performance and used the best race for further analysis. As we did not dictate which competitions the skiers participated in, these races were the only competitions all skiers participated in. All skiers used identical equipment during the laboratory testing, while we did not control the equipment used during on-snow racing, which may have affected the results. As adolescents develop rapidly at this age, the results may also have been affected by the relatively long time period between the laboratory testing and the on-snow races.

5.4.3.2 Paper II

The adolescents and juniors performed the TT_{3min} at the end of familiarization 2 while the senior athletes performed all tests in a single day due to time restrictions. However, we do not make comparisons between age-groups. We did not perform predictive analysis in this paper due to the small sample size.

5.4.3.3 Paper III

During the two maximal tests (TT_{1000m} and TT_{3min}) the skiers used wheels with a lower C_{rr} (wheel type 1) than during the sub-maximal efforts and the TT (wheel type 2). The reason for this is that wheel type 1 is the standard for the regular test protocol TT_{1000m} and the same wheel type was evaluated as being best suited for the main testing for the adolescents, while wheel type 2 has a C_{rr} more similar to regular XC-skiing on snow and was therefore used during the TT and sub-maximal efforts. However, this does not affect the results in the present study. Furthermore, rolling resistance has been found to be similar between treadmill and asphalt surfaces [80].

The model predicting $\dot{V}O_{2dem}$ in **paper III** assumes a linear relationship between VO_{2dem}, speed and P_{prop}. As the $\dot{V}O_2$ slow component becomes apparent during prolonged exercise at exercise intensities above the critical aerobic rate ("threshold" intensity), the model may underestimate the $\dot{V}O_{2dem}$, especially during the latter part of the race. This is further discussed in the supplemental content 2 of Gløersen et al. (2020) [1]. Further, the model does not consider potential change in *C* throughout the race. The exercise intensity was only calculated where the skiers generated propulsive force, so we do not have the complete intensity profile throughout the race and the mean $\dot{V}O_{2dem}$ for the race.

Methods to determine $\dot{V}O_{2peak}$ and ΣO_{2def} were different between groups. The senior skiers were participants in a previously published study by Gløersen et al. (2020) [1]. The TT_{1000m} test is a regular test protocol for elite male skiers in our lab and the seniors were well accustomed to the test. The initial start speed (corresponding to ~70 $mL \cdot kg^{-1} \cdot min^{-1}$) was evaluated as being not appropriate for the adolescents. Furthermore, as the adolescents had already performed the TT_{3min}, we chose to use the results from this test to keep the test load on the adolescent skiers as low as possible. Both maximal tests have been shown to be valid methods for determining $\dot{V}O_{2peak}$ during treadmill roller skiing [9] and ΣO_{2def} seems independent of the sub-techniques G2 and G3 [2,9]. The small difference in incline (6° vs. 8°) between groups may have affected ΣO_{2def} [2]. However, this possible difference should not have affected the main results of **paper III**, which involved the comparison of relative exercise intensity between the two groups.

It should be acknowledged that the adolescents only raced for approximately 40% of the time compared to the senior skiers. The difference in race length was chosen because most of the adolescents had never raced more than five km before, we wanted to keep a high ecological validity and because pacing may be affected by experience [68]. Since exercise intensity and duration are closely linked, the difference in duration could potentially affect the comparison of exercise intensity between the adolescents and seniors. However, analyses of FIS world-cup races over the last decades, (Losnegard 2013, p. 3) show that the mean speed for different individual XC-skiing competitions, ranging from 5k to 30k is not significantly different in elite XC-skiers [137]. Therefore, the findings in the present study would probably be comparable even if the seniors had competed for a shorter distance.

5.4.3.4 Paper IV

The most effective movement pattern is not identical between XC skiers and therefore technique modifications need to facilitate increased performance (or fewer injuries) to have relevance for the athlete. Therefore, performance changes should be monitored in studies on motor learning for athletes. However, although the performance of young athletes improves, this does not necessary imply that learning or beneficial technique modification have occurred, because the physical capacity of young athletes develops rapidly. A strength of **paper IV** is that we were able to control for this when simultaneously testing the dominant side of the G2 technique. As there was no improvement on the dominant side (Table 5), we propose that changes on the non-dominant side were due to improved technique and not just a change in physical capacity.

In the practice session it was difficult to control the information the athletes gave each other in the dyad group, or the thoughts of the athletes in the video group. There were three researchers involved in every training session in the video and dyad group to control the practice setting, but the observations and dialogues were not recorded or formally analyzed in these groups. Even though all intervention groups used the same cue cards, the information received and the interpretation of this information by the athletes may therefore be different. Further, it could well be that the skiers were influenced by the coaching methods of their ordinary coaches in their skiing clubs.

A limitation of **paper IV** is that testing was conducted in the laboratory, while the athletes performed the practice sessions outside on asphalt. It was not practically possible to train all athletes indoors due to the large number of athletes involved. Besides, doing so would have reduced ecological validity. Moreover, the data collection for cardiorespiratory and kinematic data required indoor testing.

We did not have a retention test, due to the advanced time-consuming performance tests and the large number of athletes. However, most of the athletes performed the post-testing session several days after the last practice session and the time from the last practice session to post-intervention test was balanced between groups. Further, a continuous motor skill task like the G2 technique is very well retained over long time intervals [138].

We only asked the athletes one question relating to enjoyment and one question on self-perception of improved technique. Our questions may therefore have reduced validity and should be interpreted with caution.

6 Practical applications

Knowledge of what capacities are required for different levels of performance in a specific sport is important for training optimization. However, people working with adolescent athletes should also be aware of variables other than physiological determinants that affect adolescent performance. The lower explanation of on-snow performance compared to treadmill performance by physiological determinants implies the need for a holistic approach to understanding the sport-specific demands in such age groups.

An important aspect to consider is that for the adolescent age group “the relative age effect” is present, and as such, athletes born early in the year are more likely to outperform skiers that are born later in the year [54,55]. Furthermore, although some anthropometrics affected performance in this thesis, anthropometric variables do not seem to predict future success [29,39] and should thus not be an area of focus during adolescence.

This thesis shows that when testing adolescent skiers (~14–15 years) coaches and testing staff may on average expect similar sex differences in physiological determinants of performance as those found in junior and senior skiers, even though our results indicate that some of the boys were not yet through PHV. Furthermore, our results demonstrate an overlap between sexes for the measured determinants, where the best female skiers have better results than the lowest-ranked male skiers. There were also large inter-individual differences in the physiological responses to the laboratory tests and to the feedback methods**.** This may imply that training to enhance physiological variables should not necessarily be differentiated based on sex, but rather that coaches should focus on tailoring training programs to target areas of most need. Individual preferences for feedback may also exist and should be taken into consideration when coaching groups of athletes. Thus, as a coach, one might potentially degrade the level of technique in some skiers if one is not paying attention to individual needs.

An even pacing for long duration endurance events like XC skiing distance races seems beneficial [61] and the higher effort for the adolescent skiers during the initial phases of the TT, compared to the older and more experienced skiers, may imply that adolescent skiers could benefit from adopting more conservative pacing to enhance their performance. As learning to optimize pacing is an important characteristic in the performance of young athletes [66,68], incorporating training in this skill could be an important part of optimizing performance for young skiers.

The close link between speed and gear selection indicates that the use of “higher gears” is associated with higher speed and thereby higher metabolic cost. Therefore, until the physiological capacity of adolescent skiers improves, it may be beneficial to adopt a different “gear selection strategy” than that used by seniors. As adolescent skiers spend more time in uphill than senior skiers, uphill endurance training and an effective uphill technique may be of greater importance for adolescent skiers compared to older and faster skiers. Hence, an improvement in G2 technique efficiency would benefit young skiers and could therefore be prioritized during training until their physiological capacity to achieve higher speeds has improved.

The adolescent skiers also changed gears more often than the seniors (18 ± 2 vs 15 ± 3 changes$\cdot$km^{-1}), mainly because the adolescents changed to G2 in several uphills when the seniors continued with G3. When investigating individual data, many adolescent skiers changed to G2 in the area where they lost the most time compared to the senior skiers. This could be due to loss of speed in the transition between gears as previously suggested [3]. Practicing efficient transitions between gears could therefore be important for performance and a skill that should be acquired during adolescence. The adolescents also changed to the tucked position at a lower speed than the seniors (9.2 ± 1.9 m$\cdot$s^{-1} vs.10.2 ± 1.4 m$\cdot$s^{-1} respectively, $P < .05$). As this difference in speed is likely maintained throughout the downhill, the adolescents could focus on more “aggressive pacing” in the transitions into downhills as previously found positive for overall performance in senior female skiers [7]. The adolescents demonstrated lower speeds when using the “high-speed gears” compared to the seniors. Although a speculation, in addition to what’s already discussed, this could be related to better balance and coordination in the seniors compared to adolescents and this could be a relevant area of focus for adolescents during training.

7 Conclusions

This thesis provides novel insight into XC ski-specific performance diagnostics in adolescent male and female competitive skiers.

The primary findings were:

I. While the majority of laboratory performance can be explained by physiological factors, on-snow performance for adolescents is to a larger extent based on multivariate factors.

II. $\dot{V}O_{2peak}$ is the most important determinant for overall XC skiing performance in both male and female adolescent skiers. However, the adolescent skiers show similar characteristics to those found in senior skiers, as greater upper-body maximal strength and BMI are important for sprint performance for both sexes.

III. The sex difference of 15-25% in XC ski performance is of a similar magnitude in adolescent, junior and senior skiers and the sex difference in $\dot{V}O_{2peak}$ is likely a major determinant in the sex difference in performance in all age-groups.

IV. Adolescent boys show a similar ability to repeatedly use and recover energy reserves at similar intensities as senior male skiers. However, higher initial effort for the adolescent skiers indicates a more pronounced positive pacing compared to their adult counterparts.

V. The lower speeds for the adolescents in uphills induced more use of G2 and more changes between gears compared to the seniors.

VI. When timing, frequency and amount of feedback are similar, coaching feedback from a competent coach seems superior in terms of combined performance, perceived enjoyment, self-perception of improved technique, and amount of self-practice performed compared to video feedback and dyad practice.

VII. Video feedback with cue cards, filmed on the athletes' own smart phones, improves sprint performance from pre-to post-intervention and could be a tool for increasing valuable individual feedback.

VIII. Work/skiing economy did not improve in any of the interventional feedback groups.

8 References

1. Gløersen Ø, Gilgien M, Dysthe DK, Malthe-Sørenssen A, Losnegard T. Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med Sci Sports Exerc.* 2020;52(4):983-992.
2. Karlsson Ø, Gilgien M, Gløersen ØN, Rud B, Losnegard T. Exercise Intensity During Cross-Country Skiing Described by Oxygen Demands in Flat and Uphill Terrain. *Front Physiol.* 2018;9:846.
3. Andersson E, Supej M, Sandbakk Ø, Sperlich B, Stöggl T, Holmberg HC. Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur J Appl Physiol.* 2010;110(3):585-595.
4. Marsland F, Mackintosh C, Holmberg HC, Anson, J, Waddington, G. Lyons, K., Chapman, D. Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition. *Plos One.* 2017;12(8):e0182262.
5. Holmberg HC. The elite cross-country skier provides unique insights into human exercise physiology. *Scand J Med Sci Spor.* 2015;25:100-109.
6. Jones TW, Lindblom HP, Karlsson Ø, Andersson EP, McGawley K. Anthropometric, Physiological, and Performance Developments in Cross-country Skiers. *Med Sci Sport Exer.* 2021;53(12):2553-2564.
7. Ihalainen S, Colyer S, Andersson E, McGawley K. Performance and Micro-Pacing Strategies in a Classic Cross-Country Skiing Sprint Race. *Front Sports Act Living.* 2020;2:77.
8. Andersson EP, Govus A, Shannon OM, McGawley K. Sex Differences in Performance and Pacing Strategies During Sprint Skiing. *Front Physiol.* 2019;10:295.
9. Losnegard T, Myklebust H, Hallen J. Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc.* 2012;44(4):673-681.
10. Sandbakk Ø, Hegge AM, Losnegard T, Skattebo O, Tønnessen E, Holmberg HC. The Physiological Capacity of the World's Highest Ranked Female Cross-country Skiers. *Med Sci Sports Exerc.* 2016;48(6):1091-1100.
11. Losnegard T, Hallen J. Physiological differences between sprint- and distance-specialized cross-country skiers. *Int J Sports Physiol Perform.* 2014;9(1):25-31.
12. Strøm Solli G, Kocbach J, Bucher Sandbakk S, Haugnes P, Losnegard T, Sandbakk Ø. Sex-based differences in sub-technique selection during an international classical cross-country skiing competition. *Plos One.* 2020;15(9):e0239862.
13. Sandbakk Ø, Ettema G, Leirdal S, Jakobsen V, Holmberg HC. Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur J Appl Physiol.* 2011;111(6):947-957.
14. Sandbakk Ø, Losnegard T, Skattebo Ø, Hegge AM, Tønnessen E, Kocbach J. Analysis of Classical Time-Trial Performance and Technique-Specific Physiological Determinants in Elite Female Cross-Country Skiers. *Front Physiol.* 2016;7:326.
15. Sandbakk Ø, Ettema G, Holmberg HC. Gender differences in endurance performance by elite cross-country skiers are influenced by the contribution from poling. *Scand J Med Sci Sports.* 2014;24(1):28-33.
16. Talsnes RK, Solli GS, Kocbach J, Torvik PØ, Sandbakk Ø. Laboratory- and field-based performance-predictions in cross-country skiing and roller-skiing. *Plos One.* 2021;16(8):e0256662.
17. Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G. The physiology of world-class sprint skiers. *Scand J Med Sci Sports.* 2011;21(6):e9-16.

18. Losnegard T. Energy system contribution during competitive cross-country skiing. *Eur J Appl Physiol.* 2019;119(8):1675-1690.
19. Bergeron MF, Mountjoy M, Armstrong N, et al. International Olympic Committee consensus statement on youth athletic development. *Br J Sports Med.* 2015;49(13):843-851.
20. Losnegard T, Myklebust H, Spencer M, Hallen J. Seasonal variations in VO2max, O2-cost, O2-deficit, and performance in elite cross-country skiers. *J Strength Cond Res.* 2013;27(7):1780-1790.
21. Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G. Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *Eur J Appl Physiol.* 2010;109(3):473-481.
22. Sandbakk Ø, Holmberg HC. A reappraisal of success factors for Olympic cross-country skiing. *Int J Sports Physiol Perform.* 2014;9(1):117-121.
23. Losnegard T. Strength Training for Cross-Country Skiers. In: Schumann M, Rønnestad BR, eds. *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications.* Cham: Springer International Publishing; 2019:357-368.
24. Bassett DR, Jr., Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc.* 2000;32(1):70-84.
25. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol.* 2008;586(1):35-44.
26. di Prampero PE. Factors limiting maximal performance in humans. *Eur J Appl Physiol.* 2003;90(3-4):420-429.
27. Sandbakk Ø, Holmberg HC. Physiological Capacity and Training Routines of Elite Cross-Country Skiers: Approaching the Upper Limits of Human Endurance. *Int J Sports Physiol Perform.* 2017;12(8):1003-1011.
28. Carlsson M, Carlsson T, Hammarström D, Tiivel T, Malm C, Tonkonogi M. Validation of physiological tests in relation to competitive performances in elite male distance cross-country skiing. *J Strength Cond Res.* 2012;26(6):1496-1504.
29. Zoppirolli C, Modena R, Fornasiero A, et al. Talent development in young cross-country skiers: longitudinal analysis of anthropometric and physiological characteristics. *Front Sports Active Liv.* 2020;2:111.
30. Ingjer F. Development of maximal oxygen uptake in young elite male cross-country skiers: a longitudinal study. *J Sports Sci.* 1992;10(1):49-63.
31. Landgraff HW, Riiser A, Lihagen M, Skei M, Leirstein S, Hallen J. Longitudinal changes in maximal oxygen uptake in adolescent girls and boys with different training backgrounds. *Scand J Med Sci Sports.* 2021;31 Suppl 1:65-72.
32. Armstrong N, Welsman J. Sex-Specific Longitudinal Modeling of Youth Peak Oxygen Uptake. *Pediatr Exerc Sci.* 2019;31(2):204-212.
33. Naughton G, Farpour-Lambert NJ, Carlson J, Bradney M, Van Praagh E. Physiological issues surrounding the performance of adolescent athletes. *Sports Med.* 2000;30(5):309-325.
34. Losnegard T, Myklebust H, Hallen J. No differences in O2-cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines. *J Strength Cond Res.* 2012;26(5):1340-1347.
35. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med.* 2004;34(7):465-485.
36. Losnegard T, Tosterud OK, Trøen E, Carlsen CH, Paulsen G, Rud B. The influence of pole lengths on O2-cost, kinematics, and performance in double poling at high speeds before and after a training period with long poles. *Eur J Appl Physiol.* 2019;119(11-12):2579-2587.

37. Ainegren M, Carlsson P, Tinnsten M, Laaksonen MS. Skiing economy and efficiency in recreational and elite cross-country skiers. *J Strength Cond Res.* 2013;27(5):1239-1252.
38. Ariens GA, van Mechelen W, Kemper HC, Twisk JW. The longitudinal development of running economy in males and females aged between 13 and 27 years: the Amsterdam Growth and Health Study. *Eur J Appl Physiol Occup Physiol.* 1997;76(3):214-220.
39. de Koning JJ, Bakker FC, de Groot G, van Ingen Schenau GJ. Longitudinal development of young talented speed skaters: physiological and anthropometric aspects. *J Appl Physiol (1985).* 1994;77(5):2311-2317.
40. Losnegard T, Mikkelsen K, Rønnestad BR, Hallen J, Rud B, Raastad T. The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. *Scand J Med Sci Sports.* 2011;21(3):389-401.
41. Stöggl T, Müller E, Ainegren M, Holmberg HC. General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand J Med Sci Sports.* 2011;21(6):791-803.
42. Perez-Gomez J, Rodriguez GV, Ara I, et al. Role of muscle mass on sprint performance: gender differences? *Eur J Appl Physiol.* 2008;102(6):685-694.
43. Østeras H, Helgerud J, Hoff J. Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *Eur J Appl Physiol.* 2002;88(3):255-263.
44. Hoff J, Helgerud J, Wisløff U. Maximal strength training improves work economy in trained female cross-country skiers. *Med Sci Sports Exerc.* 1999;31(6):870-877.
45. Skattebo Ø, Hallen J, Rønnestad BR, Losnegard T. Upper body heavy strength training does not affect performance in junior female cross-country skiers. *Scand J Med Sci Sports.* 2016;26(9):1007-1016.
46. McNarry M, Jones A. The influence of training status on the aerobic and anaerobic responses to exercise in children: a review. *Eur J Sport Sci.* 2014;14 Suppl 1:S57-68.
47. Gaskill SE, Serfass RC, Rundell KW. Upper body power comparison between groups of cross-country skiers and runners. *Int J Sports Med.* 1999;20(5):290-294.
48. Stöggl R, Muller E, Stöggl T. Motor abilities and anthropometrics in youth cross-country skiing. *Scand J Med Sci Sports.* 2015;25(1):e70-81.
49. Behringer M, Vom Heede A, Matthews M, Mester J. Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Pediatr Exerc Sci.* 2011;23(2):186-206.
50. Sandbakk Ø, Solli GS, Holmberg HC. Sex Differences in World-Record Performance: The Influence of Sport Discipline and Competition Duration. *Int J Sports Physiol Perform.* 2018;13(1):2-8.
51. Handelsman DJ. Sex differences in athletic performance emerge coinciding with the onset of male puberty. *Clin Endocrinol (Oxf).* 2017;87(1):68-72.
52. Senefeld JW, Clayburn AJ, Baker SE, Carter RE, Johnson PW, Joyner MJ. Sex differences in youth elite swimming. *Plos One.* 2019;14(11).
53. Cunningham LN. Physiologic comparison of adolescent female and male cross-country runners. *Ped Exerc Sci.*. 1990;2(4):313-321.
54. Müller L, Hildebrandt C, Raschner C. The Role of a Relative Age Effect in the 7(th) International Children's Winter Games 2016 and the Influence of Biological Maturity Status on Selection. *J Sports Sci Med.* 2017;16(2):195-202.
55. Raschner C, Muller L, Hildebrandt C. The role of a relative age effect in the first winter Youth Olympic Games in 2012. *Br J Sports Med.* 2012;46(15):1038-1043.

56. Handelsman DJ, Hirschberg AL, Bermon S. Circulating Testosterone as the Hormonal Basis of Sex Differences in Athletic Performance. *Endocr Rev.* 2018;39(5):803-829.
57. Joyner MJ. Physiological limits to endurance exercise performance: influence of sex. *J Physiol.* 2017;595(9):2949-2954.
58. McGawley K, Holmberg HC. Aerobic and Anaerobic Contributions to Energy Production Among Junior Male and Female Cross-Country Skiers During Diagonal Skiing. *Int J Sport Physiol.* 2014;9(1):32-40.
59. Hegge AM, Bucher E, Ettema G, Faude O, Holmberg HC, Sandbakk Ø. Gender differences in power production, energetic capacity and efficiency of elite crosscountry skiers during wholebody, upperbody, and arm poling. *Eur J Appl Physiol.* 2016;116(2):291-300.
60. Sandbakk Ø, Ettema G, Leirdal S, Holmberg HC. Gender differences in the physiological responses and kinematic behaviour of elite sprint cross-country skiers. *Eur J Appl Physiol.* 2012;112(3):1087-1094.
61. Abbiss CR, Laursen PB. Describing and understanding pacing strategies during athletic competition. *Sports Med.* 2008;38(3):239-252.
62. Losnegard T, Kjeldsen K, Skattebo Ø. An Analysis of the Pacing Strategies Adopted by Elite Cross-Country Skiers. *J Strength Cond Res.* 2016;30(11):3256-3260.
63. Skorski S, Abbiss CR. The Manipulation of Pace within Endurance Sport. *Front Physiol.* 2017;8.
64. Konings MJ, Hettinga FJ. Pacing Decision Making in Sport and the Effects of Interpersonal Competition: A Critical Review. *Sports Med.* 2018;48(8):1829-1843.
65. Menting SGP, Hendry DT, Schiphof-Godart L, Elferink-Gemser MT, Hettinga FJ. Optimal Development of Youth Athletes Toward Elite Athletic Performance: How to Coach Their Motivation, Plan Exercise Training, and Pace the Race. *Front Sports Act Liv.* 2019;1(14).
66. Elferink-Gemser MT, Hettinga FJ. Pacing and Self-regulation: Important Skills for Talent Development in Endurance Sports. *Int J Sport Physiol.* 2017;12(6):831-835.
67. Foster C, Hendrickson KJ, Peyer K, et al. Pattern of developing the performance template. *Br J Sports Med.* 2009;43(10):765-769.
68. Wiersma R, Stoter IK, Visscher C, Hettinga FJ, Elferink-Gemser MT. Development of 1500-m Pacing Behavior in Junior Speed Skaters: A Longitudinal Study. *Int J Sport Physiol.* 2017;12(9):1224-1231.
69. Stöggl T, Pellegrini B, Holmberg HC. Pacing and predictors of performance during cross-country skiing races: A systematic review. *J Sport Health Sci.* 2018;7(4):381-393.
70. Bolger CM, Kocbach J, Hegge AM, Sandbakk Ø. Speed and heart-rate profiles in skating and classical cross-country skiing competitions. *Int J Sports Physiol Perform.* 2015;10(7):873-880.
71. Welde B, Stöggl TL, Mathisen GE, et al. The pacing strategy and technique of male cross-country skiers with different levels of performance during a 15-km classical race. *Plos One.* 2017;12(11).
72. Carlsson T, Carlsson M, Hammarström D, Rønnestad BR, Malm CB, Tonkonogi M. Optimal $\dot{V}O_{2max}$-to-mass ratio for predicting 15 km performance among elite male cross-country skiers. *J Sports Med.* 2015;6:353-360.
73. Nikolaidis PT, Villiger E, Knechtle B. Older recreational cross-country skiers adopt more even pacing strategies than their younger counterparts of similar performance level. *Res Sports Med.* 2019;27(3):365-373.
74. Nikolaidis PT, Villiger E, Rosemann T, Knechtle B. The effect of aging on pacing strategies of cross-country skiers and the role of performance level. *Eur Rev Aging Phys Act.* 2018;15:4.

75. Gaul CA, Docherty D, Cicchini R. Differences in anaerobic performance between boys and men. *Int J Sports Med.* 1995;16(7):451-455.
76. Zwiren LD. Anaerobic and aerobic capacities of children. *Ped Exerc Science.* 1989;1(1):31-44.
77. Lees A. Technique analysis in sports: a critical review. *J Sports Sci.* 2002;20(10):813-828.
78. Nilsson J, Tveit P, Eikrehagen O. Cross-Country Skiing: Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomech.* 2004;3(1):85-108.
79. Nilsson J, Tveit P, Eikrehagen O. Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomech.* 2004;3(1):85-107.
80. Gløersen Ø, Losnegard T, Malthe-Sørenssen A, Dysthe DK, Gilgien M. Propulsive Power in Cross-Country Skiing: Application and Limitations of a Novel Wearable Sensor-Based Method During Roller Skiing. *Front Physiol.* 2018;9:1631.
81. Stöggl T, Holmberg HC. Three-dimensional Force and Kinematic Interactions in V1 Skating at High Speeds. *Med Sci Sports Exerc.* 2015;47(6):1232-1242.
82. Andersson E, Holmberg HC, Ørtenblad N, Bjorklund G. Metabolic Responses and Pacing Strategies during Successive Sprint Skiing Time Trials. *Med Sci Sports Exerc.* 2016;48(12):2544-2554.
83. Frederick E. Mechanical constraints on Nordic ski performance. *Med Sci Sports Exerc.* 1992;24(9):1010-1014.
84. Smith G, Kvamme B, Jakobsen V. *Effectiveness of ski and pole forces in ski skating.* Conference paper. 2009.
85. Solli GS, Kocbach J, Seeberg TM, et al. Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *Plos One.* 2018;13(11).
86. Van der Kamp J, Duivenvoorden J, Kok M, van Hilvoorde I. Motor skill learning in groups: Some proposals for applying implicit learning and self-controlled feedback. *RICYDE Revista Inter de Cienc del Depe.* 2015;11(39):33-47.
87. Ste-Marie DM, Law B, Rymal AM, Jenny O, Hall C, McCullagh P. Observation interventions for motor skill learning and performance: an applied model for the use of observation. *Int Rev Sport Exerc Psychol.* 2012;5(2):145-176.
88. Myklebust H, Losnegard T, Hallen J. Differences in V1 and V2 ski skating techniques described by accelerometers. *Scand J Med Sci Sports.* 2014;24(6):882-893.
89. Magill R, Anderson D. Motor learning and control: concepts and applications. 2011. In: New York: McGraw-Hill Higher Education.
90. Porter JM, Wu W, Partridge JA. Focus of attention and verbal instructions: Strategies of elite track and field coaches and athletes. *Sport Sci Rev.* 2010;19(3-4):199-211.
91. Cumming J, Clark SE, Ste-Marie DM, McCullagh P, Hall C. The functions of observational learning questionnaire (FOLQ). *Psychol Sport Exerc.* 2005;6(5):517-537.
92. Shea CH, Wright DL, Wulf G, Whitacre C. Physical and observational practice afford unique learning opportunities. *J Mot Behav.* 2000;32(1):27-36.
93. Shea CH, Wulf G, Whitacre C. Enhancing Training Efficiency and Effectiveness Through the Use of Dyad Training. *J Mot Behav.* 1999;31(2):119-125.
94. Lee TD, Swinnen SP, Serrien DJ. Cognitive Effort and Motor Learning. *Quest.* 1994;46(3):328-344.
95. Nowels RG, Hewit JK. Improved Learning in Physical Education through Immediate Video Feedback. *Strategies.* 2018;31(6):5-9.

96. Williams AM, Davids K, Williams JG. *Visual perception and action in sport.* New York: E & FN Spon; 1999.
97. D'Innocenzo G, Gonzalez CC, Williams AM, Bishop DT. Looking to Learn: The Effects of Visual Guidance on Observational Learning of the Golf Swing. *Plos One.* 2016;11(5):e0155442.
98. Kernodle MW, Carlton LG. Information feedback and the learning multiple-degree-of-freedom activities. *J Mot Behav.* 1992;24(2):187-196.
99. Janelle CM, Champenoy JD, Coombes SA, Mousseau MB. Mechanisms of attentional cueing during observational learning to facilitate motor skill acquisition. *J Sports Sci.* 2003;21(10):825-838.
100. Smith GA, Nelson RC, Feldman A, Rankinen JL. Analysis of V1 skating technique of Olympic cross-country skiers. *Inter J Sport Biomech.* 1989;5(2):185-207.
101. Norman R, Ounpuu S, Fraser M, Mitchell R. Mechanical power output and estimated metabolic rates of Nordic skiers during Olympic competition. *Inter J of Sport Biomech.* 1989;5(2):169-184.
102. Hoffman MD, Clifford PS. Physiological responses to different cross country skiing techniques on level terrain. *Med sci sports and exercise.* 1990;22(6):841-848.
103. Smith GA, McNitt-Gray J, Nelson RC. Kinematic analysis of alternate stride skating in cross-country skiing. *Inter J Sport Biomech.* 1988;4(1):49-58.
104. Smith GA, Nelson RC. Effects of increased velocity on the kinematics of V1 skating in cross country skiing. Paper presented at: ISBS-Conference Proceedings Archive1988.
105. Ainegren M, Carlsson P, Tinnsten M. An experimental study to compare the grip of classical style roller skis with on-snow skiing. *Sports Eng.* 2013;16(2):115-122.
106. Sandbakk O, Ettema G, Leirdal S, Jakobsen V, Holmberg HC. Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur J Appl Physiol.* 2011;111(6):947-957.
107. Myklebust H. Quantification of movement patterns in cross-country skiing using inertial measurement units. [Dissertation]. 2016.
108. Stöggl T, Holst A, Jonasson A, et al. Automatic classification of the sub-techniques (gears) used in cross-country ski skating employing a mobile phone. *Sensors (Basel).* 2014;14(11):20589-20601.
109. Marsland F, Lyons K, Anson J, Waddington G, Macintosh C, Chapman D. Identification of cross-country skiing movement patterns using micro-sensors. *Sensors.* 2012;12(4):5047-5066.
110. Aughey RJ. Applications of GPS technologies to field sports. *Int J sports physiol perf.* 2011;6(3):295-310.
111. Larsson P, Henriksson-Larsén K. Combined metabolic gas analyser and dGPS analysis of performance in cross-country skiing. *J sports sci.* 2005;23(8):861-870.
112. Andersson E, Supej M, Sandbakk O, Sperlich B, Stoggl T, Holmberg HC. Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur J Appl Physiol.* 2010;110(3):585-595.
113. Bucher Sandbakk S, Supej M, Sandbakk Ø, Holmberg HC. Downhill turn techniques and associated physical characteristics in cross-country skiers. *Scand J med sci sports.* 2014;24(4):708-716.
114. Hoffman MD, Clifford PS, Bota B, Mandli M, Jones GM. Influence of Body-Mass on Energy-Cost of Roller Skiing. *Int J Sport Biomech.* 1990;6(4):374-385.
115. Borg G. *Physical performance and perceived exertion* [Dissertation]. Lund, Lund.; 1962.
116. FIS. FIS Cross-Country Homologation Manual. In: FIS, ed2019.

117. Gilgien M, Sporri J, Limpach P, Geiger A, Müller E. The Effect of Different Global Navigation Satellite System Methods on Positioning Accuracy in Elite Alpine Skiing. *Sensors-Basel.* 2014;14(10):18433-18453.
118. Wulf G, Shea C, Lewthwaite R. Motor skill learning and performance: a review of influential factors. *Med Educ.* 2010;44(1):75-84.
119. Wulf G, Lewthwaite R. Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychon Bull Rev.* 2016;23(5):1382-1414.
120. Andersson EP, McGawley K. A Comparison between Different Methods of Estimating Anaerobic Energy Production. *Front Physiol.* 2018;9:82.
121. Cohen J. Statistical power analysis for the social sciences. 1988.
122. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc.* 2009;41(1):3-13.
123. Dunn OJ. Multiple comparisons using rank sums. *Technometrics.* 1964;6(3):241-252.
124. Norman RW, Komi PV. Mechanical Energetics of World Class Cross-Country Skiing. *Int J Sport Biomech.* 1987;3(4):353-369.
125. Sollie O, Gløersen Ø, Gilgien M, Losnegard T. Differences in pacing pattern and sub-technique selection between young and adult competitive cross-country skiers. *Scand J Med Sci Sports.* 2020;31(3):553-563.
126. Andersson E, Björklund G, Holmberg HC, Örtenblad N. Energy system contributions and determinants of performance in sprint cross-country skiing. *Scand J Med Sci Sports.* 2017;27(4):385-398.
127. Nikolaidis PT, Rosemann T, Knechtle B. The differences in pacing among age groups of amateur cross-country skiers depend on performance. *J hum kinetics.* 2019;66:165.
128. Pellegrini B, Zoppirolli C, Bortolan L, Holmberg HC, Zamparo P, Schena F. Biomechanical and energetic determinants of technique selection in classical cross-country skiing. *Hum Mov Sci.* 2013;32(6):1415-1429.
129. Smith G, Kvamme B, Jakobsen V. *Effectiveness of ski and pole forces in ski skating.* Maidenhead (UK): Meyer & Meyer Sport; 2009.
130. Gastin PB. Energy system interaction and relative contribution during maximal exercise. *Sports Med.* 2001;31(10):725-741.
131. Hegge AM, Myhre K, Welde B, Holmberg HC, Sandbakk Ø. Are gender differences in upper-body power generated by elite cross-country skiers augmented by increasing the intensity of exercise? *Plos One.* 2015;10(5):e0127509.
132. Ericsson KA, Krampe RT, Teschromer C. The Role of Deliberate Practice in the Acquisition of Expert Performance. *Psychol Rev.* 1993;100(3):363-406.
133. Knoblich G, Flach R. Predicting the effects of actions: interactions of perception and action. *Psychol Sci.* 2001;12(6):467-472.
134. Mueller D, Georges A, Vaslow D. Cooperative learning as applied to resident instruction in radiology reporting. *Acad Radiol.* 2007;14(12):1577-1583.
135. Thorrud S. Is laterality, intensity or strength asymmetry associated with the preferred side in the G2 skating technique in cross-country skiing? 2013.
136. Foss O, Hallen J. Validity and stability of a computerized metabolic system with mixing chamber. *Int J Sports Med.* 2005;26(7):569-575.
137. Losnegard T. *Physiological determinants of performance in modern elite cross-country skiing* [Norwegian School of Sport Sciences]2013.

138. Schmidt RA, Lee TD, Winstein C, Wulf G, Zelaznik HN. *Motor control and learning: A behavioral emphasis.* Human kinetics; 2018.
139. Sarrazin P, Biddle S, Famose JP, Cury F, Fox K, Durand M. Goal orientations and conceptions of the nature of sport ability in children: A social cognitive approach. *Brit J Soc Psychol.* 1996;35:399-414.
140. Ommundsen Y. Implicit theories of ability and self-regulation strategies in physical education classes. *Educational Psychology.* 2003;23(2):141-157.
141. Toering T, Jordet G, Ripegutu A. Effective learning among elite football players: the development of a football-specific self-regulated learning questionnaire. *J Sports Sci.* 2013;31(13):1412-1420.

9 Appendixes

69

9.1 Appendix 1 - Supplementary material in paper I

Comparison of top and bottom tertile for determinants

Supplementary methods

The boys and girls were ranked by TT_{3min} performance. The top- and bottom-ranked tertiles (top and bottom third of the ranking) were compared using two-tailed, independent samples *t* tests for the determinants. The Holm-Šídák method was used for multiple comparisons. A level of $P \leq 0.05$ was considered significant. Statistical analyses were performed using Graphpad Prizm 9 (GraphPad Software, San Diego, CA).

Age was calculated in weeks from the date of birth to the day of testing and converted back to years. $\dot{V}O_{2peak}$ and ΣO_{2def} were calculated from the TT_{3min}; leg-press and pull-down were measured from a one-repetition maximum test; and gross efficiency was calculated from steady state exercise. Strength was tested separately for each arm and leg to determine whether there was a difference in strength between the right and left side. As there was no difference between right and left sides, the mean of both sides is presented.

Supplementary tables

Table 6. Comparison of top- and bottom-ranked tertile in boys

Determinants	Top tertile (Mean ± SD)	Bottom tertile (Mean ± SD)	Difference	*P*-value
$TT3_{min}$ performance (m)	518 ± 23	402 ± 28	116	< 0.01
Age (years)	15.1 ± 0.4	14.3 ± 0.6	0.8	< 0.01
Body weight (kg)	62.4 ± 7.7	53.3 ± 5.3	9.1	0.01
Body height (cm)	174 ± 7	168 ± 4	6	0.05
BMI ($kg \cdot min^2$)	20.4 ± 1.5	18.8 ± 1.3	1.6	0.02
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	66.3 ± 3.6	57.7 ± 5.6	8.6	< 0.01
ΣO_{2def} ($ml \cdot kg^{-1}$)	73 ± 10	51 ± 16	22	< 0.01
ΣO_{2def} of tot. req. (%)	47 ± 10	35 ± 12	12	0.04
Leg-press ($kg \cdot BW^{-1}$)	1.76 ± 0.3	1.54 ± 0.3	0.22	0.16
Pull-down ($kg \cdot BW^{-1}$)	0.25 ± 0.06	0.22 ± 0.0	0.03	< 0.01
Gross efficiency (%)	17.2 ± 0.9	15.9 ± 1.2	1.3	0.03

BMI = Body mass index; ΣO_{2def} = accumulated oxygen deficit; ΣO_{2def} of tot. req. = accumulated oxygen deficit in percentage of total energy requirements; BW = body weight

Table 7. Comparison of top- and bottom-ranked tertiles in girls

Determinants	Top tertile (Mean ± SD)	Bottom tertile (Mean ± SD)	Difference	*P*-value
$TT3_{min}$ performance (m)	434 ± 24	354 ± 20	80	< 0.01
Age (years)	14.6 ± 0.6	14.8 ± 0.5	-0.2	0.57
Body weight (kg)	53.9 ± 5.7	61.0 ± 8.3	-7.1	0.05
Body height (cm)	166 ± 6	170 ± 6	-4	0.21
BMI ($kg \cdot min^2$)	19.6 ± 1.7	21.2 ± 2.6	-1.6	0.13
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	59 ± 5	51 ± 6	8	<0.01
ΣO_{2def} ($ml \cdot kg^{-1}$)	58 ± 12	34 ± 14	24	<0.01
ΣO_{2def} of tot. req. (%)	40 ± 11	27 ± 12	13	0.03
Leg-press ($kg \cdot BW^{-1}$)	1.76 ± 0.4	1.50 ± 0.3	0.26	0.12
Pull-down ($kg \cdot BW^{-1}$)	0.22 ± 0.0	0.20 ± 0.0	0.02	0.28
Gross efficiency (%)	16.7 ± 1.4	16.7 ± 1.3	-0.0	0.96

BMI = Body mass index; ΣO_{2def} = accumulated oxygen deficit; ΣO_{2def} of tot. req. = accumulated oxygen deficit in percentage of total energy requirements; BW = body weight

9.2 Appendix 2 – Multiple regression analysis

The full stepwise multiple regression analysis of $\dot{V}O_{2peak}$ relative to bodyweight (model 1), ΣO_{2def} relative to bodyweight (model 2) and GE (model 3) explained >80% of the variation in TT_{3min} performance in the boys and the girls. For the sprint performance, the full model explained less than 20% of the variation and was not significant in either boys or girls. For the distance performance, the full model explained ~30% of the variation in the boys and girls (Table 8).

Table 8. Full stepwise multiple regression analysis of $\dot{V}O_{2peak}$ relative to bodyweight (model 1), ΣO_{2def} relative to bodyweight (model 2) and GE (model 3).

	1[a]		2[a,b]		3[a,b,c]	
	Boys	Girls	Boys	Girls	Boys	Girls
TT_{3min}	**Full model:** Boys $F_{(3,22)}$ = 43.3, P < .01; Girls $F_{(2,20)}$ = 23.2, P < .01					
R^2	.57	.42	.78	.57	.86	.78
R^2 *change*	.57	.42	.21	.15	.07	.20
P value	< .001	< .001	< .001	.012	.003	< .001
Distance performance	**Full model:** Boys $F_{(3,22)}$ = 3.1, P = .05; Girls $F_{(3,20)}$ = 3.4, P = .04					
R^2	.28	.25	.30	.26	.30	.34
R^2 *change*	.28	.25	.02	.01	.00	.08
P value	.005	.012	.470	.680	.873	.138
Sprint performance	**Full model:** Boys $F_{(3, 22)}$ = 1.5, P = .24; Girls $F_{(3, 19)}$ = 1.5, P = .25					
R^2	.17	.14	.17	.18	.17	.19
R^2 *change*	.17	.14	.00	.04	.17	.01
P value step	.038	.077	.900	.749	.24	.25

a: $\dot{V}O_{2peak}$, b: ΣO_{2def}, c: Gross efficiency, Distance performance = 5 km for girls and 14-year-old boys (~12-16 min) and 7.5 km for 15-year old boys (~19-20 min), Sprint performance = ~1 km (2.5-3 min).

9.3 Appendix 3 – Difference between dominant and non-dominant side

Table 9 shows the statistical difference with effect size between the dominant and the non-dominant side pre-intervention in **paper IV.** There was a difference between sides for all tests, but the effect size increased with higher speed.

Table 9. Pre-intervention difference between the dominant and non-dominant side for different performance scores.

	% dif. between sides ± 95 % CI	***P***	**Cohens *d***
Sub-maximal skiing economy	1.4 ± 0.8	.001	.10, very small effect
VO_{2peak}	1.7 ± 1.3	.01	.16, very small effect
TT_{3min} performance	5.8 ± 1.6	<.001	.49, small effect
Incremental speed test	6.2 ± 0.9	<.001	.86, large effect

Data are mean and 95% CI

9.4 Appendix 4 – Questionnaires

The questionnaires were answered during the main test, between the treadmill roller skiing and the maximal strength tests. First questionnaire was about conceptions of ability and is based on Sarrazin et al. (1996) [139] and the Norwegian translated version from Ommundsen (2001) [140]. The second questionnaire was about self-regulation and based on Toering et a. (2013) [141]. Third and fourth questionnaire was about self-reported training and preferred side respectively. The last questionnaire was about the participants overall feeling at the day of testing.

Om langrennsteknikk De fleste langrennsløpere har en god og en mindre god hengside i padling. Spørsmålene under handler om den mindre gode hengsiden. Sett et kryss i passende boks ved siden av spørsmålene. Les spørsmålene nøye før du svarer.		**Helt enig**	**Litt enig**	**Litt enig/ Litt uenig**	**Litt uenig**	**Helt uenig**
1	Man har et visst nivå i padling på den mindre gode hengsiden, og det er egentlig ikke så mye man kan gjøre for å forandre det.	☐	☐	☐	☐	☐
2	Selv om du prøver, vil padlingen på den mindre gode hengsiden forandre seg lite	☐	☐	☐	☐	☐
3	Dersom du øver og strever lenge og regelmessig med å forbedre padling på den mindre gode hengsiden, blir du helt klart bedre	☐	☐	☐	☐	☐
4	Padling på den mindre gode hengsiden er svært vanskelig å forbedre	☐	☐	☐	☐	☐
5	Padlingen på den mindre gode hengsiden vil forbedres dersom du jobber med det	☐	☐	☐	☐	☐
6	Det er vanskelig å gjøre noe med nivået sitt i padling på den mindre gode hengsiden	☐	☐	☐	☐	☐
7	Dersom du anstrenger deg nok, vil padlingen på den mindre gode hengsiden automatisk bli bedre.	☐	☐	☐	☐	☐

	Tanker om teknikk Alle spørsmålene omhandler hva du tenker om padleteknikken på den mindre gode hengsiden	**Aldri**	**Sjelden**	**Noen ganger**	**Ofte**	**Alltid**
1	På hver trening tenker jeg på mine styrker og svakheter, og måter jeg kan forbedre de på	☐	☐	☐	☐	☐
2	Under hver treningsøkt sjekker jeg om jeg har framgang	☐	☐	☐	☐	☐
3	Jeg kjenner mine styrker og svakheter, og på hver treningsøkt planlegger jeg hvordan jeg kan forbedre de	☐	☐	☐	☐	☐
4	Under hver treningsøkt følger jeg med på hvordan jeg presterer i forhold til mitt treningsmål (så jeg ser hvor jeg står)	☐	☐	☐	☐	☐
5	På hver treningsøkt prøver jeg å identifisere mine styrker, og tenker på måter jeg kan utvikle disse enda mer	☐	☐	☐	☐	☐
6	På hver treningsøkt jobber jeg med mine styrker og svakheter fordi jeg tror på mitt potensial	☐	☐	☐	☐	☐
7	På hver trening fokuserer jeg på mitt treningsmål	☐	☐	☐	☐	☐
8	Under hver treningsøkt sjekker jeg hva jeg fortsatt må gjøre for å nå mitt treningsmål	☐	☐	☐	☐	☐
9	På hver treningsøkt prøver jeg å identifisere mine svakheter, og tenke på hvordan jeg kan forbedre disse	☐	☐	☐	☐	☐
10	Etter hver trening tenker jeg tilbake og evaluerer (vurderer) om jeg gjorde de riktige tingene for å bli bedre	☐	☐	☐	☐	☐
11	Jeg har et individuelt mål før hver trening	☐	☐	☐	☐	☐
12	Etter hver trening tenker jeg tilbake på situasjoner som oppsto under treningen, og bruker denne informasjonen til å trene på spesifikke ting alene eller med andre	☐	☐	☐	☐	☐
13	Før hver trening planlegger jeg hvilke ferdigheter jeg ønsker å jobbe med på treningsøkta	☐	☐	☐	☐	☐
14	På hver trening bruker jeg informasjon fra utøvere jeg har sett på TV/internett/live til å bli bedre	☐	☐	☐	☐	☐
15	Før hver trening planlegger jeg handlingene mine i forhold til målet jeg vil oppnå i løpet av treningsøkta	☐	☐	☐	☐	☐
16	Etter hver trening tenker jeg tilbake og evaluerer (vurderer) om jeg har gjort de rette tingene for å nå mitt treningsmål	☐	☐	☐	☐	☐
17	På hver trening bruker jeg informasjon fra bøker, aviser og intervjuer fra topputøvere for å utvikle meg	☐	☐	☐	☐	☐
18	Jeg følger med på mine prestasjoner på hver trening, slik at jeg kan se hvilke deler av teknikken jeg må forbedre	☐	☐	☐	☐	☐
19	Jeg kommer til hver trening for å jobbe med spesifikke ferdigheter	☐	☐	☐	☐	☐
20	Etter hver trening tenker jeg på hva jeg gjorde rett og galt under treningsøkta	☐	☐	☐	☐	☐
21	Jeg blir igjen etter hver trening for å jobbe med spesifikke ferdigheter	☐	☐	☐	☐	☐
22	Etter hver trening tenker jeg tilbake på spesifikke situasjoner under treninga og hva jeg gjorde rett eller galt	☐	☐	☐	☐	☐

	Om trening Ta deg god til å svare på spørsmålene. Det er viktig du prøver å svare så riktig som mulig og ikke legger på ekstra treningstid i spørsmålene.	
1	Hvor mye trener du ca. per uke i gjennomsnitt gjennom året?	Timer: Minutter:
2	Hvor mye trente du ca. per uke den siste måneden?	Timer: Minutter:
3	Hvor mange timer av svaret i spørsmål 1 er utholdenhetstrening og kondisjonstrening?	Timer: Minutter:
4	Hvor mange treningsøkter trener du ca. per uke?	Antall:
5	Hvor lenge ca. varer hver treningsøkt i gjennomsnitt?	Ant. Min:
6	Hvor mange treningsøkter i uka er på rulleski (både klassisk og skøyting)?	Antall:
7	Hvor mange treningsøkter i uka er rulleski skøyting?	Antall:
8	Hvor mange minutter tror du at du bruker i padling på en treningsøkt med rulleski skøyting?	Ant. Min:
9	Hvor mange minutter fra svaret fra spørsmål 8 tror du at du bruker på den «dårlige» hengsiden?	Ant. Min:

	Om foretrukket side			
1	På hvilken side padler du best (foretrukket hengside)? – sett kryss	**Venstre** ☐	**Høyre** ☐	**Begge/Ingen foretrukket** ☐
2	På hvilken side foretrekker du å «hente» taket i enkeldans (siden hvor du setter ned begge stavene samtidig som du skyver med det ene beinet)? – sett kryss	**Venstre** ☐	**Høyre** ☐	**Begge/Ingen foretrukket** ☐
3	Hvilken hånd foretrekker du å skrive med? – sett kryss	**Venstre** ☐	**Høyre** ☐	**Begge/Ingen foretrukket** ☐
4	Hvilken arm foretrekker du å kaste med? – sett kryss	**Venstre** ☐	**Høyre** ☐	**Begge/Ingen foretrukket** ☐
5	Hvilken fot foretrekker du å sparke en fotball med? – sett kryss	**Venstre** ☐	**Høyre** ☐	**Begge/Ingen foretrukket** ☐
6	Hvis du skal bruke en spade i en sandhaug. Hvilken side av kroppen vil du føle det naturlig å bruke spaden på (siden med den bakerste hånden på spaden)?	**Venstre** ☐	**Høyre** ☐	**Begge/Ingen foretrukket** ☐
7	Hvis du skulle balansere på en fot på en tynn tømmerstokk, hvilken fot tror du ville vært lettest å balansere på?	**Venstre** ☐	**Høyre** ☐	**Begge/Ingen foretrukket** ☐
8	Hvis du skulle tråkke opp på en høy stol, hvilken fot ville du synes var lettest å bruke?	**Venstre** ☐	**Høyre** ☐	**Begge/Ingen foretrukket** ☐

	Om dagsform	
1	Hvor mange timer sov du i natt?	Timer: Minutter:
2	Hvor godt sov du i natt på en skala fra 1-10 hvor 1 er dårligst og 10 er best – ring rundt	1 2 3 4 5 6 7 8 9 10
3	Hvordan føler du din dagsform har vært på en skala fra 1-10 hvor 1 er dårligst og 10 er best – ring rundt	1 2 3 4 5 6 7 8 9 10

9.5 Appendix 5 - Approval letter from the Ethical committee

Ove Sollie

Seksjon for fysisk prestasjonsevne | OSLO 09. august 2017

Søknad 08-080817 – Teknikkanalyse av forskjellige aldersgrupper og teknisk utvikling blant unge langrennsløpere

Vi viser til vedtak fra Etisk komite, Norges idrettshøgskole, datert 15. juni 2017 hvor det ble bedt om at søknad 08-130617 sendes på nytt etter at NSD har behandlet søknaden datert 24. mai 2017.

Videre vises det til innsendt søknad datert 18. juli 2017 med prosjektbeskrivelse, informasjonsskriv og godkjenningsbrev datert 30. juni 2017 fra NSD. I henhold til retningslinjer for behandling av søknad til etisk komite for idrettsvitenskapelig forskning på mennesker, har komiteen konkludert med følgende:

Vedtak

På bakgrunn av forelagte dokumentasjon finner komiteen at prosjektet er forsvarlig og at det kan gjennomføres innenfor rammene av anerkjente forskningsetiske normer nedfelt i NIHs retningslinjer.

Til vedtaket har komiteen lagt følgende forutsetning til grunn:

- *At vilkår fra NSD følges*

Komiteen gjør oppmerksom på at vedtaket er avgrenset i tråd med fremlagte dokumentasjon. Dersom det gjøres vesentlige endringer i prosjektet som kan ha betydning for deltakernes helse og sikkerhet, skal dette legges fram for komiteen før eventuelle endringer kan iverksettes.

Med vennlig hilsen
Professor Sigmund Loland
Leder, Etisk komite, Norges idrettshøgskole

9.6 Appendix 6 – Approval notification of change

Thomas Losnegaard
Seksjon for fysisk prestasjonsevne

OSLO 03. september 2018

Endringsmelding 08-130617 – 300818 -Teknikkanalyse av forskjellige aldersgrupper og teknisk utvikling blant unge langrennsløpere

Vi viser til endringsmelding for prosjekt 08-130617.

Vedtak

På bakgrunn av forelagte dokumentasjon har komiteen godkjent den omsøkte endring fra prosjektleder vedrørende nytt forsøk og datainnsamling i prosjektet (deltakelse i rulleskikonkurranse for gutter 14-15 år).

Med vennlig hilsen
Professor Sigmund Loland
Leder, Etisk komite, Norges idrettshøgskole

9.7 Appendix 7 – Approval from the Norwegian Centre for Research Data

Ove Sollie
Seksjon for fysisk prestasjonsevne Norges idrettshøgskole
Postboks 4014
0806 OSLO

Vår dato: 30.06.2017 Vår ref: 54517 / 3 / AMS Deres dato: Deres ref:

TILBAKEMELDING PÅ MELDING OM BEHANDLING AV PERSONOPPLYSNINGER

Vi viser til melding om behandling av personopplysninger, mottatt 24.05.2017. Meldingen gjelder prosjektet:

54517	*Teknikkanalyse av forskjellige aldersgrupper og teknisk utvikling blant unge langrennsløpere*
Behandlingsansvarlig	*Norges idrettshøgskole, ved institusjonens øverste leder*
Daglig ansvarlig	*Ove Sollie*

Personvernombudet har vurdert prosjektet, og finner at behandlingen av personopplysninger vil være regulert av § 7-27 i personopplysningsforskriften. Personvernombudet tilrår at prosjektet gjennomføres.

Personvernombudets tilråding forutsetter at prosjektet gjennomføres i tråd med opplysningene gitt i meldeskjemaet, korrespondanse med ombudet, ombudets kommentarer samt personopplysningsloven og helseregisterloven med forskrifter. Behandlingen av personopplysninger kan settes i gang.

Det gjøres oppmerksom på at det skal gis ny melding dersom behandlingen endres i forhold til de opplysninger som ligger til grunn for personvernombudets vurdering. Endringsmeldinger gis via et eget skjema, http://www.nsd.uib.no/personvernombud/meld_prosjekt/meld_endringer.html. Det skal også gis melding etter tre år dersom prosjektet fortsatt pågår. Meldinger skal skje skriftlig til ombudet.

Personvernombudet har lagt ut opplysninger om prosjektet i en offentlig database, http://pvo.nsd.no/prosjekt.

Personvernombudet vil ved prosjektets avslutning, 30.06.2021, rette en henvendelse angående status for behandlingen av personopplysninger.

Vennlig hilsen

Kjersti Haugstvedt

Anne-Mette Somby

Kontaktperson: Anne-Mette Somby tlf: 55 58 24 10
Vedlegg: Prosjektvurdering

Dokumentet er elektronisk produsert og godkjent ved NSDs rutiner for elektronisk godkjenning.

NSD – Norsk senter for forskningsdata AS Harald Hårfagres gate 29 Tel: +47-55 58 21 17 nsd@nsd.no Org.nr. 985 321 884
NSD – Norwegian Centre for Research Data NO-5007 Bergen, NORWAY Faks: +47-55 58 96 50 www.nsd.no

Papers I-IV

Paper I

Anthropometrical and physiological determinants of laboratory and on-snow performance in competitive adolescent cross-country skiers

Ove Sollie[1*], Thomas Losnegard[1]

[1] Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway

*** Correspondence:**
Ove Sollie, Department of Physical Performance, Norwegian School of Sport Sciences
Sognsveien 220, PO Box 4014 Ulleval Stadion, 0806 Oslo, Norway.
Telephone: +47 23262311
Email: ove.sollie@nih.no

Keywords: $\dot{V}O_{2peak}$, Gross efficiency, Anaerobic capacity, Strength, Talent development, Maximal aerobic power, Time trial, upper-body power

Abstract

Purpose:

To explore the anthropometrical and physiological determinants of laboratory and on-snow performance in competitive adolescent cross-country skiers.

Methods:

Fifty-two adolescent (25 girls) (14.8 ± 0.6 years) skiers performed an uphill treadmill rollerski session using the G2 ski skating technique. Gross efficiency (GE) was calculated from a submaximal work bout (~84% of peak oxygen uptake; $\dot{V}O_{2peak}$) while $\dot{V}O_{2peak}$, accumulated oxygen deficit (ΣO_{2def}) and laboratory performance were determined from a 3-min time trial (TT_{3min}) before upper- and lower-body maximum strength were tested. Pearson's product moment correlations and multiple regression analysis explored the relationship with anthropometrical and physiological determinations of laboratory and on-snow performance in sprint (~1 km, ~2.5-3 min) and distance races (5-7.5 km, ~12-20 min) from the national championship for this age-group.

Results:

A large correlation was found between on-snow sprint and distance performance (boys r=.61, girls r=.76, both P<.01) and for on-snow distance performance with TT_{3min} (r=.51 to .56, P<.05). $\dot{V}O_{2peak}$, ΣO_{2def} and GE explained ~80% of variations in performance in the TT_{3min}, but substantial lower on-snow skiing performance (~20-30%). For the TT_{3min} performance, $\dot{V}O_{2peak}$ showed a very large and large correlation for boys and girls (r=.76 and .65 respectively, both P<.01) and ΣO_{2def} showed a large correlation for boys and girls (r=.53 and .55 respectively, both P<.01). Age showed a large correlation for boys (r=.56, P<.01), with no significant correlation for girls (r=-.19). For on-snow distance performance, $\dot{V}O_{2peak}$ showed a large correlation for boys (r=.53, P<.01) and girls (r=.50, P<.05). For on-snow sprint performance, upper-body strength (r=.55, both sexes P<.01) and body mass index (BMI) showed a large correlation for boys (r=.53, P<.01) and girls (r=.51, P<.05).

Conclusion:

$\dot{V}O_{2peak}$ is the most important determinant for overall XC skiing performance in competitive male and female adolescent skiers. However, upper-body strength and BMI correlate the most with sprint performance. While laboratory performance can be explained by physiological factors, on-snow-performance for adolescents is based on multivariate factors, implying the need for a holistic approach to understanding the sport-specific demands in such age-groups.

Introduction

Performance in endurance sports is mainly determined by the metabolic energy turnover (energy · $time^{-1}$) divided by the energy cost of locomotion (energy · $distance^{-1}$). Cross country (XC) skiing is a demanding and complex whole-body endurance sport that consists of races performed on undulating terrain with highly varying exercise intensity and complex interactions in energy system contributions [1,2]. Physiological determinants including peak oxygen uptake ($\dot{V}O_{2peak}$) [3-5], the ability to efficiently transform metabolic energy into speed (e.g., gross efficiency (GE)) [3,6] and the ability to repeatedly perform, and recover from, efforts above the $\dot{V}O_{2peak}$ [1,2] are all important for XC skiing performance. Depending on the race length, sub-technique used and the technical ability of the skiers, a certain level of strength also seems necessary to optimize performance [7]. Moreover, differences in racing distances (durations can be between ~3 min and ~2 h) differentiate the magnitude of importance between these physiological determinants to some extent [8]. A substantial body of research has examined these physiological demands in (male) junior and senior XC skiers, but there are few studies of these measures in adolescent XC skiers.

Adolescent skiers (14-15 yrs) compete in the sprint (~1 km, ~2.5-3 min) and distance (5-7.5 km, ~12-20 min) format, often on similar racecourses to those used by senior skiers. The physiological determinants of performance are possibly similar, with similar magnitudes of importance for adolescent as for senior skiers. However, anthropometric, physiological, and biomechanical differences exist between adolescent and adult skiers, and the timing of physiological development differs between adolescent boys and girls [9]. Better understanding of these determinants for adolescent skiers could provide important insights for optimizing the training process and the design of performance tests for adolescent XC skiers.

As for senior skiers, $\dot{V}O_{2peak}$ is a major component of performance in adolescent skiers, but growth in muscle mass, and thereby strength, appears to be a dominant factor in the increase in $\dot{V}O_{2peak}$ for these adolescent skiers [10]. Moreover, anaerobic capacity and gross efficiency are also potential important determinants of performance in adolescent skiers. Greater muscle mass and strength affects anaerobic capacity [11], and thus XC skiing performance in senior skiers [12]. Strength has further been shown to correlate with XC skiing performance [13] and may be related to improved sport-specific technique in adolescent athletes [14]. Gross efficiency (GE) is important for XC skiing performance in senior skiers [3] and has been found to be a discriminating factor for performance between performance levels in senior skiers [15]. However, it is uncertain how these determinants affect adolescent skiing performance as there is little relevant research on adolescent skiers.

From an applied perspective, successful skiing performance is not affected by a single physiological determinant in isolation, but by a combination of determinants [16,17]. Previous studies have used different determinants of performance, performance levels of participants, methodology and XC skiing sub-techniques, which have explained performance differently [18-21]. A previous study of adult male skiers showed that 66% of the variation in a ~3-min uphill skiing test could be predicted by $\dot{V}O_{2peak}$, anaerobic capacity and GE [12]. In adolescent athletes, previous research on how different physiological determinants affect performance has usually used non-specific and easily administered tests, which may not provide accurate predictions of key physiological determinants of XC skiing performance. Previous studies have explored how motor abilities and running performance [13] and roller ski performance [22] predict on-snow skiing performance in adolescent skiers, but no previous studies have used advanced laboratory measurements.

XC ski training consists of a substantial amount of on-snow and roller ski specific training [23] and there is little research relating to ski-specific performance diagnostics in adolescent XC skiers. We therefore aimed to explore how age, anthropometric factors and key physiological determinants of endurance performance (i.e. $\dot{V}O_{2peak}$, anaerobic capacity, GE and strength) correlate with, and explain, laboratory and on-snow performance during sprint and distance competitions for adolescent male and female skiers.

Materials and methods

Participants

Fifty-two adolescent competitive XC skiers (27 boys and 25 girls) participated in the study (Table 1). The athletes were recruited from local XC-ski clubs in Oslo, Norway. The inclusion criteria were experience with roller skiing and participation in national XC skiing competitions. Participants and their parents were informed of the nature of the study and the possible risks involved before giving their written consent. The study was approved by the Human Research Ethics Committee of The Norwegian School of Sport Sciences and registered with the Norwegian Centre for Research Data.

<< Table 1 Around here >>

Performance level

The performance level was calculated as the percentage behind the mean time of the top three competitors from the national championships for this age group (“Hovedlandsrennet”, a national competition with participants from all over Norway). Skiers can compete in this national race for two consecutive years (age 14 and 15) and the performance level in the present study was the skiers’ best distance and sprint race times from the seasons before and after testing.

Testing

All participants were tested in the pre-season period (August-September). Testing was performed in the ski skating sub-technique G2 on a roller ski treadmill (Rodby, Sodertalje, Sweden) with dimensions of 3 × 4.5m. To exclude possible variations in rolling resistance, all skiers used the same Swenor Skate roller skis (Sport Import AS, Sarpsborg, Norway) with wheel type 1, a coefficient of friction of $\mu = 0.018$, and Rottefella binding systems (Rottefella AS, Lier, Norway) for all tests. The coefficient of friction was measured every week during the study period and was found to be consistent throughout. All participants used Swix Triac 1.0 or 3.0 poles of a self-selected length (~90% of body height) (Swix, Lillehammer, Norway), modified with a tip specifically adapted for use on a roller skiing treadmill. Participants were secured to the treadmill by a safety harness connected to an emergency brake during testing. Height, body mass and total mass including equipment were measured before each testing session (Seca model 877, Hamburg, Germany). $\dot{V}O_2$ was determined using a metabolic analyzer with mixing chamber (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany), calibrated according to the manufacturer’s instruction manual. Heart rate (HR) was measured throughout using a Polar M400 with a 1-Hz sampling rate (Kempele, Finland). Twenty-seven skiers were tested in 2017, while the remaining skiers were tested in 2018 due to the time-consuming nature of the methods. Because a difference between breath-by-breath and mixing chamber measures was found after the first round of testing [2], breath-by-breath measures of $\dot{V}O_2$ were used for 27 skiers (2017) while averaged measures (mixing chamber) were used for the remaining skiers (2018). The number of skiers tested by breath-by-breath and mixing chamber measures were balanced in both boys and girls.

Familiarization

Prior to testing, the adolescent skiers completed two sessions to familiarize them with the apparatus and the different test protocols. The first familiarization consisted of ~35 min roller ski skating at different intensities. The second familiarization session consisted of a 10-min easy self-paced warm-up and two 5-min steady-state submaximal G2 work bouts with cardiorespiratory measurements, before the skiers performed a 3-min time trial (TT_{3min}). Finally, familiarization with the strength testing protocol was conducted.

TT_{3min}

TT_{3min} was a 3-min maximal uphill time trial performed on the rollerski treadmill set to an 8° incline. The initial speed was 2.0 $m \cdot s^{-1}$ for the girls and 2.25 $m \cdot s^{-1}$ for the boys. This speed was fixed during the first 30 s to prevent the skiers from starting too fast. Thereafter, the skiers themselves controlled the speed by adjusting their position on the treadmill relative to laser beams situated in front of and behind them. Each contact between the front or back wheels of the skis and the lasers induced a 0.25 $m \cdot s^{-1}$ increase or reduction in treadmill speed, respectively, conducted manually by the test leader. Visual feedback with respect to time was provided throughout. Cardiorespiratory variables ($\dot{V}O_2$ and RER) were monitored throughout the test and analyzed for $\dot{V}O_{2peak}$, defined as the average of the six highest consecutive 5-s measurements (total 30 s).

Main test session

The main test session included multiple submaximal work bouts with different measures, as the skiers were part of a larger research project, but only relevant work bouts and measures for the present study are included here. Following a 6-min self-paced warm-up, participants completed 5-min submaximal rollerskiing at a 6° incline and a similar estimated relative intensity (~84% of $\dot{V}O_{2peak}$) and rating of perceived exertion (RPE) (RPE 15 ± 1; $\dot{V}O_2$ 84 ± 6% of $\dot{V}O_{2peak}$) for all skiers. Cardiorespiratory variables were monitored from 2–5 min and the average values were used for further analysis. RPE (Borg Scale 6-20) [24], was taken immediately after the work bout. The gross efficiency was calculated from this work bout.

Calculations of gross efficiency (GE) and accumulated oxygen deficit (ΣO_{2def})

Propulsive power on the treadmill was calculated as the sum of power against gravity and power against rolling resistance as previously described [12]. GE was calculated as the work rate divided by the metabolic rate under steady state conditions and ΣO_{2def} was given by subtracting the accumulated $\dot{V}O_2$ from the accumulated estimated $\dot{V}O_2$ requirements during TT_{3min} [25].

Strength tests

One-repetition maximum (1RM) strength tests were performed 20 min after the end of the roller ski tests using the same protocol as described by Losnegard (2011) [26]. The order of the tests was the same for all skiers. Strength was tested separately for each arm and leg to determine whether there was a difference in strength between the right and left side. All 1RM testing was supervised by the same investigator and conducted using the same equipment, with identical equipment set-up for each skier.

Single leg press: The single leg press test was performed on an inclined (45°) leg press machine. Before the test, the correct depth (90° knee angle) was measured and noted. The test started with straight legs before the skiers lowered the weights to the correct depth, at which point they received a signal from the test leader to push back up. The attempt was considered valid when the weights were returned to the starting position.

Single arm pull-down: Seating was adjusted to a 90° angle at the knees and hips, with a "neutral" spine and back resting against a backboard and both feet flat on the floor throughout the test. The "non-testing arm" rested on the opposite thigh. The pull was performed holding a custom-made ski pole grip positioned at the height of the forehead. The wire was parallel to the back support.

Participants then pulled the grip straight down, with the pull defined as valid when the hand hit the bench they were sitting on in one continuous motion, without bending the torso forward away from the backboard and with both feet kept on the ground.

Statistics

Normality of the data was assessed using the Shapiro-Wilks test (α=0.05) and visual inspection of Q-Q plots. For statistical tests, a level of $P \leq 0.05$ was considered significant and $P \leq .10$ was considered a tendency. Figures display mean ± 95% confidence interval (CI). Pearson's product moment correlations were applied for correlations. Correlation coefficients were classified as .1 to .3 small, .3 to .5 moderate, .5 to .7 large, .7 to .9 very large and >.9 extremely large [27]. Stepwise multiple regression analyses were run with $\dot{V}O_{2peak}$, ΣO_{2def} and GE as independent variables to explain the TT_{3min}, distance and sprint performance, separately. Boys and girls were analyzed separately. Statistical analyses were performed using Graphpad Prizm 9 (GraphPad Software, San Diego, CA) and SPSS statistical package version 24 (SPSS Inc. Chicago, IL).

Results

Relationship between laboratory and on-snow performance

There was a large correlation between sprint and distance performance in boys and a very large correlation in girls. Further, there was a moderate to large correlation between TT_{3min} performance and on-snow performance for both boys and girls (Fig. 1).

<< Figure 1 around here >>

Multiple regression analysis

The full stepwise multiple regression analysis of $\dot{V}O_{2peak}$ relative to bodyweight (model 1), ΣO_{2def} relative to bodyweight (model 2) and GE (model 3) explained >80% of the variation in TT_{3min} performance in the boys and the girls (Table 1). For the sprint performance, the full model explained under 20% of the variation and was not significant in the boys or the girls (Table 2). For the distance performance, the full model explained ~30% of the variation in the boys and the girls (Table 3).

<< Table 2 around here>>

<< Table 3 around here>>

<< Table 4 around here>>

Determinants of laboratory performance (TT_{3min})

For the boys, there was a large correlation between TT_{3min} performance and age and a moderate correlation for weight and height. No significant correlation was found for the girls (Fig. 2).

<< Figure 2 around here >>

There was a very large correlation between TT_{3min} performance and $\dot{V}O_{2peak}$ relative to body weight in boys and a large correlation in girls. There was a large correlation between TT_{3min} performance and ΣO_{2def} relative to body weight in boys and girls. Finally, there was a moderate correlation between TT_{3min} and GE in boys, with no significant correlation in girls (Fig. 3).

<< Figure 3 around here >>

There was a moderate correlation between TT_{3min} performance and upper-body strength in boys while a moderate correlation was found between TT_{3min} performance and leg-press strength in girls (Fig. 4).

<< Figure 4 around here >>

Determinants of on-snow performance

There was a moderate correlation between sprint performance and weight in boys and a large correlation between sprint performance and BMI in boys and girls. Distance performance did not significantly correlate with age, weight, height or BMI for either boys or girls (Fig. 5).

<< Figure 5 around here >>

There was a moderate correlation between sprint performance and $\dot{V}O_{2peak}$ relative to body weight in boys and a large correlation between distance performance and $\dot{V}O_{2peak}$ relative to body weight in boys and girls. Neither sprint nor distance performance was significantly correlated to ΣO_{2def} relative to body weight and GE in either boys or girls (Fig. 6).

<< Figure 6 around here >>

There was a large correlation between sprint performance and pull-down strength in boys and girls. Further, distance performance and pull-down strength was also moderately correlated in girls (Fig. 7).

<< Figure 7 around here >>

Total training volume had a very large correlation with TT_{3min} ($r = .81$, $P < .05$), and a large correlation with sprint ($r = -.53$, $P < .05$) and distance ($r = -.56$, $P < .05$) performance in boys (not shown in figures). No significant correlation was found in girls ($r = -.25$, $-.09$ and $-.16$, TT_{3min}, sprint and distance respectively).

Discussion

We explored how anthropometrics and key physiological determinants of XC ski performance related to treadmill roller skiing and on-snow sprint and distance performance in competitive adolescent male and female skiers. In this study, $\dot{V}O_{2peak}$, ΣO_{2def} and GE explained ~80% of the TT_{3min} performance in both sexes, which is somewhat higher than previously reported for a ~3-min TT [12] and similar to a ~4-min TT [3] in elite senior skiers. However, the present study highlights the complexity of on-snow skiing performance, where only a small part of the variation in performance (~20-30%) can be explained by $\dot{V}O_{2peak}$, ΣO_{2def} and GE. This discrepancy in explaining laboratory and on-snow performance is probably due to numerous factors such as the topography of the course, tactics, the quality of the equipment and weather and snow conditions, and shows that on-snow performance is based on multivariate factors and implies the need for a holistic approach for understanding the sport-specific demands in such age groups.

The strong relationship between sprint and distance performance indicates that there is an overlap in determinants of performance for adolescent skiers in these two disciplines. $\dot{V}O_{2peak}$ relative to body weight explained a large proportion of the variation alone in the TT_{3min} and on-snow distance performance, and contributed substantially to sprint performance. Thus, in line with results from adult skiers [5,8], $\dot{V}O_{2peak}$ is an important determinant of adolescent skiing performance. The reason why some adolescents have higher $\dot{V}O_{2peak}$ than others is debated [10]. A large training volume through adolescence has previously been related to a high $\dot{V}O_{2peak}$ [28] and increased performance [10]. However, more specific endurance training during adolescence does not necessary produce a higher $\dot{V}O_{2peak}$ compared with similar volumes of training mainly aimed at developing motor skills [10]. Our research design did not allow for detailed analysis of how training is related to performance, but it is worth noting that self-reported total training hours for the boys had a large to very large correlation for the three performance settings and a large correlation with $\dot{V}O_{2peak}$ relative to body weight (r = .56). Hence, higher training volumes with a focus on developing fundamental and sport-specific motor skills [10] should probably be evaluated as a major part of the training in adolescent skiers.

Increased muscle mass, and thereby strength, in adolescent skiers also appears to be a dominant factor in the increase in $\dot{V}O_{2peak}$ [10] and an explanatory variable to be associated with maturity status [29]. We did not have any maturity measures in the present study, but increased weight in these well-trained boys most likely relates to increased growth-related muscle-mass. Further, it seemed that age and weight were more important for laboratory performance in the boys than in the girls. When ranking the skiers based on TT_{3min} performance and comparing the top and bottom ranked tertile in the boys, the top tertile were significantly older, heavier and taller compared to the bottom tertile (see appendix for methodological explanation). This was not apparent in the girls, and unlike the boys, the top-performing tertile in the girls was lighter than the bottom tertile (see appendix). This shows that boys born early in the year (relative age effect) and maturing early (i.e. greater muscle mass) had a performance advantage compared to those who were born and matured later. The relative age effect has also been previously shown in adolescent winter sport athletes [30,31] and maturity status has previously been found to be a major confounding variable for performance in male adolescent skiers [13] with an estimated peak height velocity (PHV) between 13.8 [10] and 14.2 yrs [13]. Although this is ~5-9 months younger than the boys in the present study, this may indicate that many of the boys in the present study were in the period around PHV. Girls mature earlier than boys, and the PHV for female adolescent skiers is estimated to be ~12.2 yrs [10,13]. Most of the girls in the present study were thereby likely past PHV, and the top- and bottom-performing tertile were more similar in age and anthropometrics than the boys. Regardless, anthropometric variables do not seem to predict future success [32,33] and should thus not be an area of focus during adolescence.

Previous studies have shown different physiological demands for senior sprint and distance skiing [8,34], where higher muscle mass and anaerobic capacity have been found in senior sprint skiers compared to performance-matched distance skiers [8]. Similar characteristics were found for the adolescent skiers in the present study, as $\dot{V}O_{2peak}$ relative to body weight was highly related to both laboratory and on-snow distance performance, while upper-body strength and BMI contributed most to sprint performance in both sexes. Upper-body power has also previously been observed as a determinant of performance in both senior [34] and adolescent [13] skiers, probably related to the close relationship between muscle mass and anaerobic capacity [11,12]. However, the correlation found between ΣO_{2def} and TT_{3min} performance in the present study was not present in on-snow performance. ΣO_{2def} found in laboratory time trials may not reflect how anaerobic capacity is used during real-world skiing competitions where anaerobic capacity per se might not reflect skiing performance, but rather the ability to repeatedly use and recover the energy reserves represented by the oxygen deficits [2].

GE did not have a strong relationship with performance in the present study. This is in line with a recent study in senior male skiers, showing a trivial correlation between GE and outdoor performance [19]. However, GE has previously been found to be a discriminating factor between junior and senior skiers [15]. Furthermore, improved GE has been shown to improve XC skiing performance, highlighting that GE is very important for skiing performance [3,35]. However, the complexity of the skiing techniques and thereby a possibly large inter-individual variation in technical solutions, together with the influence of intrinsic factors [36], might diminish the discriminating effect of GE on performance in the present and other studies [5,19].

Limitations

We included no maturation measures in the present study and as age and anthropometrics were related to TT_{3min} and sprint performance in boys and not girls, maturity is thus a possible confounder for performance in the boys. For on-snow performance, we only assessed two races in each racing format (sprint and distance) for each skier, where we eliminated the worst performance and used the best race for further analysis. As we did not dictate which competitions the skiers participated in, these races were the only competitions all skiers participated in. All skiers used identical equipment during the laboratory testing, while we did not control the equipment used during on-snow racing, which might have affected the results. As adolescents develop rapidly at this age, the results may also have been affected by the relatively long time period between the laboratory testing and the on-snow races.

Conclusion

In competitive male and female adolescent skiers, on-snow sprint and distance performance differ in physiological demands, as $\dot{V}O_{2peak}$ is the single most important determinant for distance skiing while upper-body strength and BMI are the most important determinants for sprint performance. $\dot{V}O_{2peak}$, ΣO_{2def} and GE explained ~80% of the TT_{3min} performance, but only a small part of the variation in on-snow sprint and distance performance (~20-30%). This shows that adolescent XC skiing performance is based on multivariate factors, implying the need for a holistic approach to understanding the sport-specific demands in such age-groups.

References

1. Sollie O, Gløersen Ø, Gilgien M, Losnegard T. Differences in pacing pattern and sub-technique selection between young and adult competitive cross-country skiers. *Scand J Med Sci Sports.* 2020;31(3):553-563.
2. Gløersen Ø, Gilgien M, Dysthe DK, Malthe-Sørenssen A, Losnegard T. Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med Sci Sports Exerc.* 2020;52(4):983-992.
3. Losnegard T, Myklebust H, Spencer M, Hallen J. Seasonal variations in VO2max, O2-cost, O2-deficit, and performance in elite cross-country skiers. *J Strength Cond Res.* 2013;27(7):1780-1790.
4. Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G. The physiology of world-class sprint skiers. *Scand J Med Sci Sports.* 2011;21(6):e9-16.
5. Sandbakk Ø, Hegge AM, Losnegard T, Skattebo O, Tønnessen E, Holmberg HC. The Physiological Capacity of the World's Highest Ranked Female Cross-country Skiers. *Med Sci Sports Exerc.* 2016;48(6):1091-1100.
6. Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G. Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *Eur J Appl Physiol.* 2010;109(3):473-481.
7. Losnegard T. Strength Training for Cross-Country Skiers. In: Schumann M, Rønnestad BR, eds. *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications.* Cham: Springer International Publishing; 2019:357-368.
8. Losnegard T, Hallen J. Physiological differences between sprint- and distance-specialized cross-country skiers. *Int J Sports Physiol Perform.* 2014;9(1):25-31.
9. Naughton G, Farpour-Lambert NJ, Carlson J, Bradney M, Van Praagh E. Physiological issues surrounding the performance of adolescent athletes. *Sports Med.* 2000;30(5):309-325.
10. Landgraff HW, Riiser A, Lihagen M, Skei M, Leirstein S, Hallen J. Longitudinal changes in maximal oxygen uptake in adolescent girls and boys with different training backgrounds. *Scand J Med Sci Sports.* 2021;31 Suppl 1:65-72.
11. Perez-Gomez J, Rodriguez GV, Ara I, et al. Role of muscle mass on sprint performance: gender differences? *Eur J Appl Physiol.* 2008;102(6):685-694.
12. Losnegard T, Myklebust H, Hallen J. Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc.* 2012;44(4):673-681.
13. Stöggl R, Muller E, Stöggl T. Motor abilities and anthropometrics in youth cross-country skiing. *Scand J Med Sci Sports.* 2015;25(1):e70-81.
14. Behringer M, Vom Heede A, Matthews M, Mester J. Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Pediatr Exerc Sci.* 2011;23(2):186-206.
15. Ainegren M, Carlsson P, Tinnsten M, Laaksonen MS. Skiing economy and efficiency in recreational and elite cross-country skiers. *J Strength Cond Res.* 2013;27(5):1239-1252.
16. Losnegard T. Energy system contribution during competitive cross-country skiing. *Eur J Appl Physiol.* 2019;119(8):1675-1690.
17. Hebert-Losier K, Zinner C, Platt S, Stoggl T, Holmberg HC. Factors that Influence the Performance of Elite Sprint Cross-Country Skiers. *Sports Med.* 2017;47(2):319-342.
18. Mahood NV, Kenefick RW, Kertzer R, Quinn TJ. Physiological determinants of cross-country ski racing performance. *Med Sci Sports Exerc.* 2001;33(8):1379-1384.
19. Talsnes RK, Solli GS, Kocbach J, Torvik PØ, Sandbakk Ø. Laboratory- and field-based performance-predictions in cross-country skiing and roller-skiing. *Plos One.* 2021;16(8):e0256662.
20. Larsson P, Olofsson P, Jakobsson E, Burlin L, Henriksson-Larsen K. Physiological predictors of performance in cross-country skiing from treadmill tests in male and female subjects. *Scand J Med Sci Sports.* 2002;12(6):347-353.
21. Jones TW, Lindblom HP, Karlsson Ø, Andersson EP, McGawley K. Anthropometric, Physiological, and Performance Developments in Cross-country Skiers. *Med Sci Sport Exer.* 2021;53(12):2553-2564.
22. Stöggl R, Muller E, Stöggl T. Do Maximal Roller Skiing Speed and Double Poling Performance Predict Youth Cross-Country Skiing Performance? *J Sports Sci Med.* 2017;16(3):383-390.
23. Sandbakk Ø, Holmberg HC. A reappraisal of success factors for Olympic cross-country skiing. *Int J Sports Physiol Perform.* 2014;9(1):117-121.
24. Borg G. *Physical performance and perceived exertion* [Dissertation]. Lund, Lund.; 1962.
25. Andersson EP, McGawley K. A Comparison between Different Methods of Estimating Anaerobic Energy Production. *Front Physiol.* 2018;9:82.
26. Losnegard T, Mikkelsen K, Rønnestad BR, Hallen J, Rud B, Raastad T. The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. *Scand J Med Sci Sports.* 2011;21(3):389-401.
27. Hopkins WG. A new view of statistics; A Scale of Magnitudes for Effect Statistics. http://www.sportsci.org/resource/stats/effectmag.html. Published 2002. Accessed 17.04.2020.
28. Ingjer F. Development of maximal oxygen uptake in young elite male cross-country skiers: a longitudinal study. *J Sports Sci.* 1992;10(1):49-63.
29. McNarry M, Jones A. The influence of training status on the aerobic and anaerobic responses to exercise in children: a review. *Eur J Sport Sci.* 2014;14 Suppl 1:S57-68.
30. Müller L, Hildebrandt C, Raschner C. The Role of a Relative Age Effect in the 7(th) International Children's Winter Games 2016 and the Influence of Biological Maturity Status on Selection. *J Sports Sci Med.* 2017;16(2):195-202.
31. Raschner C, Muller L, Hildebrandt C. The role of a relative age effect in the first winter Youth Olympic Games in 2012. *Br J Sports Med.* 2012;46(15):1038-1043.
32. de Koning JJ, Bakker FC, de Groot G, van Ingen Schenau GJ. Longitudinal development of young talented speed skaters: physiological and anthropometric aspects. *J Appl Physiol (1985).* 1994;77(5):2311-2317.

33. Zoppirolli C, Modena R, Fornasiero A, et al. Talent development in young cross-country skiers: longitudinal analysis of anthropometric and physiological characteristics. *Frontiers in Sports and Active Living.* 2020;2:111.
34. Carlsson M, Carlsson T, Hammarström D, Tiivel T, Malm C, Tonkonogi M. Validation of physiological tests in relation to competitive performances in elite male distance cross-country skiing. *J Strength Cond Res.* 2012;26(6):1496-1504.
35. Losnegard T, Tosterud OK, Trøen E, Carlsen CH, Paulsen G, Rud B. The influence of pole lengths on O2-cost, kinematics, and performance in double poling at high speeds before and after a training period with long poles. *Eur J Appl Physiol.* 2019;119(11-12):2579-2587.
36. Losnegard T, Myklebust H, Hallen J. No differences in O2-cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines. *J Strength Cond Res.* 2012;26(5):1340-1347.

Tables

Table 1. Participants' characteristics.

	Boys (n=27)	**Girls (n=25)**
Age (years)*	14.7 ± 0.6	14.8 ± 0.5
Body mass (kg)	57.2 ± 7.7	56.6 ± 7.8
Body height (cm)	172 ± 7	167 ±5
BMI (kg·m^2)	19.3 ± 1.6	20.3 ± 2.5
$\dot{V}O_{2peak}$ (ml·kg^{-1}·min^{-1})	62.1 ± 5.6	53.9 ± 5.9
Weekly training (h)**	9.3 ± 3.6	8.9 ± 3.2

Data is reported as mean ± standard deviation. *Age was calculated in weeks from the date of birth to the day of testing and converted back to years. **Weekly training was self-reported. VO_{2peak} = ski specific (roller ski) maximal oxygen uptake. VO_{2peak} was measured on the dominant side in the G2 skating technique. BMI = Body mass index

Table 2. Full stepwise multiple regression analysis of $\dot{V}O_{2peak}$ (model 1), ΣO_{2def} (model 2), GE (model 3) for TT_{3min} performance.

Model	*Sex*	*R^2*	***Change statistics***	
			R^2 change	F statistic
1^a	Boys	.57	.57	$F_{1,24}$ = 32.2, P < .001
	Girls	.42	.42	$F_{1,22}$ = 16.0, P < .001
2^{a,b}	Boys	.78	.21	$F_{1,23}$ = 22.1, P < .001
	Girls	.57	.15	$F_{1,21}$ = 7.5, P = .012

3[a,b,c]	Boys	.86	.07	$F_{1,22}$ = 11.1, *P* = .003
	Girls	.78	.20	$F_{1,20}$ = 18.2, *P* < .001
Full model	Boys			$F_{(3,22)}$ = 43.3, *P* < .01
	Girls			$F_{(2,20)}$ = 23.2, *P* < .01

a: $\dot{V}O_{2peak}$, b: ΣO_{2def}, c: Gross efficiency

Table 3. Full stepwise multiple regression analysis of $\dot{V}O_{2peak}$ (model 1), ΣO_{2def} (model 2), GE (model 3) for sprint performance.

Model	*Sex*	R^2	***Change statistics***	
			R^2 change	F statistic
1[a]	Boys	.17	.17	$F_{1,24}$ = 4.8, *P* = .038
	Girls	.14	.14	$F_{1,21}$ = 3.5, *P* = .077
2[a,b]	Boys	.17	.00	$F_{1,23}$ = .0, *P* = .900
	Girls	.18	.04	$F_{1,20}$ = 1.0, *P* = .319
3[a,b,c]	Boys	.17	.00	$F_{1,22}$ = .1, *P* = .771
	Girls	.19	.01	$F_{1,19}$ = .1, *P* = .749
Full model	Boys			$F_{(3, 22)}$ = 1.5, *P* = .24
	Girls			$F_{(3, 19)}$ = 1.5, *P* = .25

a: $\dot{V}O_{2peak}$, b: ΣO_{2def}, c: Gross efficiency

Table 4. Full stepwise multiple regression analysis of $\dot{V}O_{2peak}$ (model 1), ΣO_{2def} (model 2), GE (model 3) for distance performance.

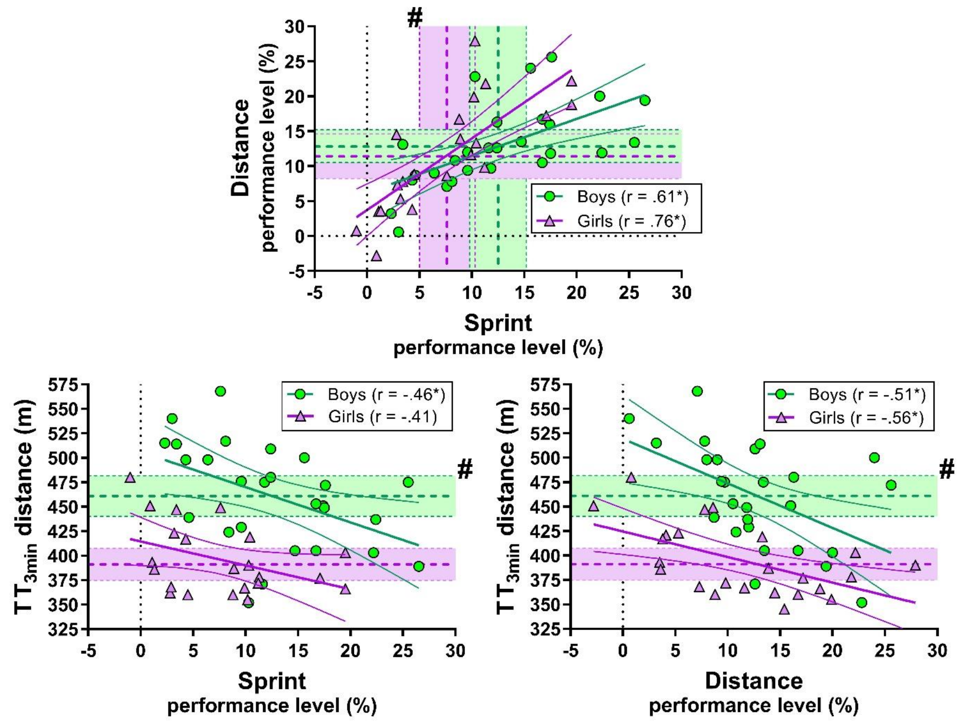
Model	*Sex*	R^2	***Change statistics***	
			R^2 change	F statistic
1[a]	Boys	.28	.28	$F_{1,24}$ = 9.5, *P* = .005
	Girls	.25	.25	$F_{1,22}$ = 7.4, *P* = .012

2[a,b]	Boys	.30	.02	$F_{1,23}$ = .5, *P* = .470
	Girls	.26	.01	$F_{1,21}$ = .2, *P* = .680
3[a,b,c]	Boys	.30	.00	$F_{1,22}$ = .0, *P* = .873
	Girls	.34	.08	$F_{1,20}$ = 2.4, *P* = .138
Full model	Boys			$F_{(3,22)}$ = 3.1, *P* = .05
	Girls			$F_{(3,20)}$ = 3.4, *P* = .04

a: $\dot{V}O_{2peak}$, b: ΣO_{2def}, c: Gross efficiency (GE)

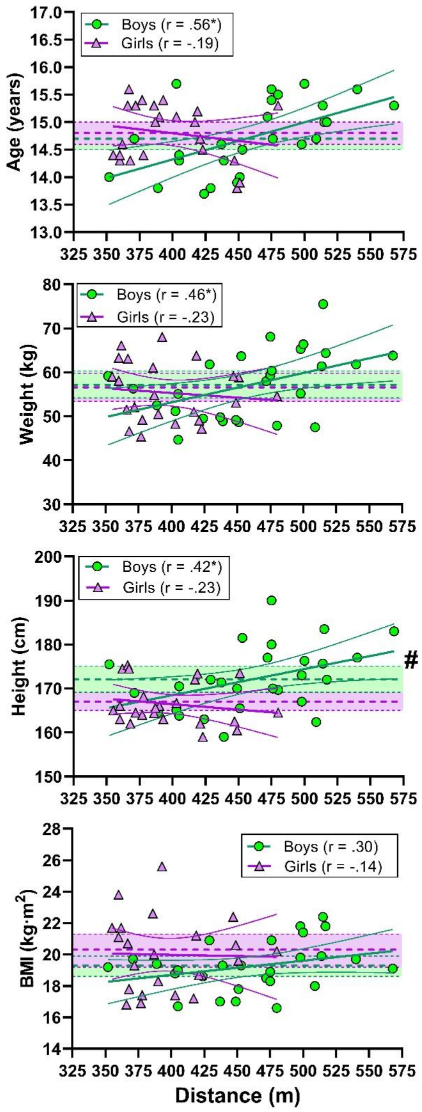
Figure captions

Figure 1.



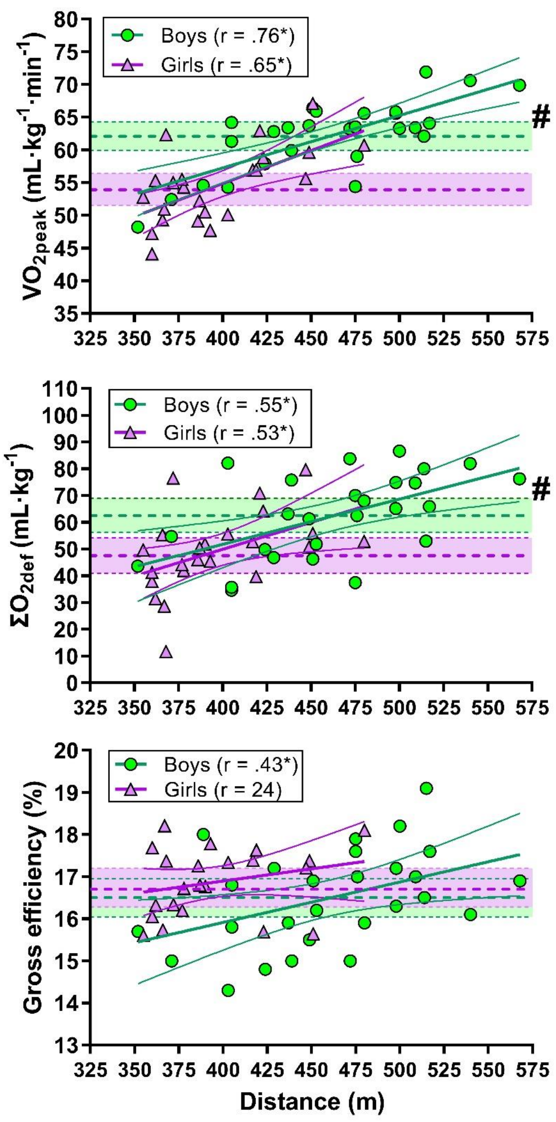
Correlation between sprint and distance performance (upper panel) and sprint and distance performance in TT_{3min} (lower panel). Green circles represent individual values for the boys. Purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI). Green is used for the boys and purple for the girls. For distance vs. sprint performance (upper panel) the horizontal shaded area represents mean ± 95% for distance performance and the vertical shaded area represents mean ± 95% for sprint performance. Thick and narrow lines represent the best fit regression line and the 95% confidence bands (green lines for the boys and purple for the girls). See the method section for an explanation of the performance level. * Correlation is significant at the .05 level. # significant difference between boys and girls.

Figure 2.



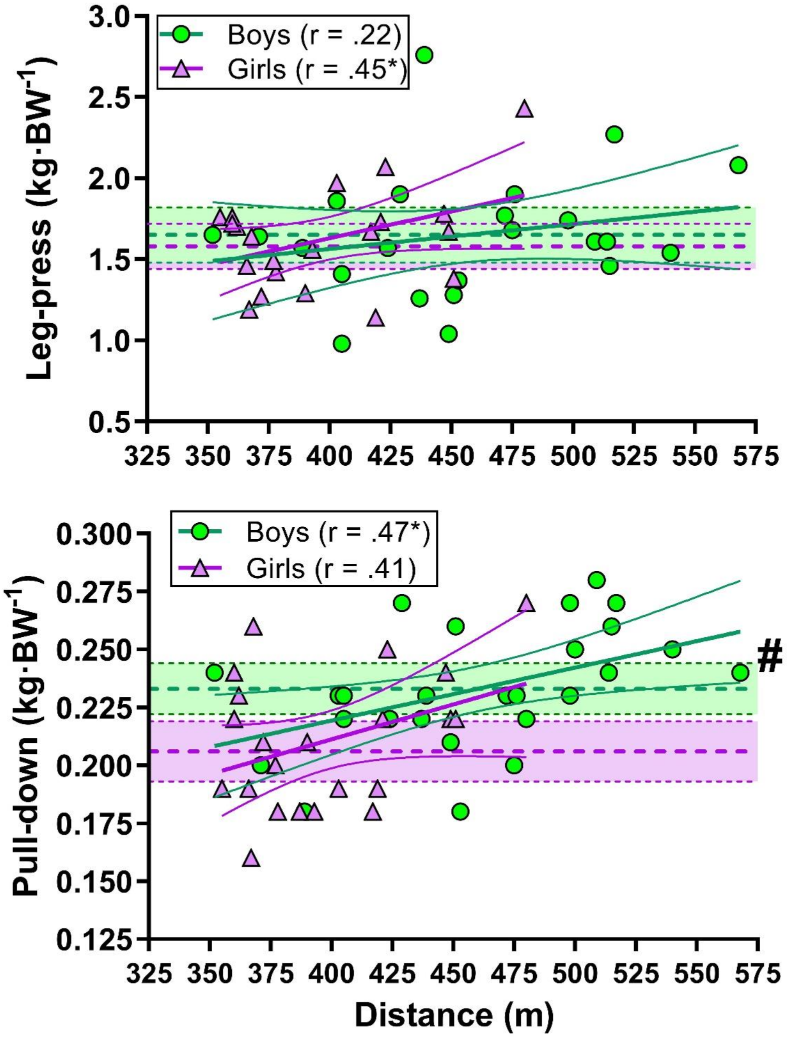
Correlations between indoor rollerski 3-min maximal uphill (8°) time-trial (TT_{3min}) performance and age, weight, height and BMI. Green circles represent individual values for the boys and purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green areas for the boys and purple for the girls). Thick and narrow lines represent the best fit regression lines and the 95% confidence bands (green lines for the boys and purple for the girls). * Correlation is significant at the .05 level. # significant difference between boys and girls.

Figure 3.



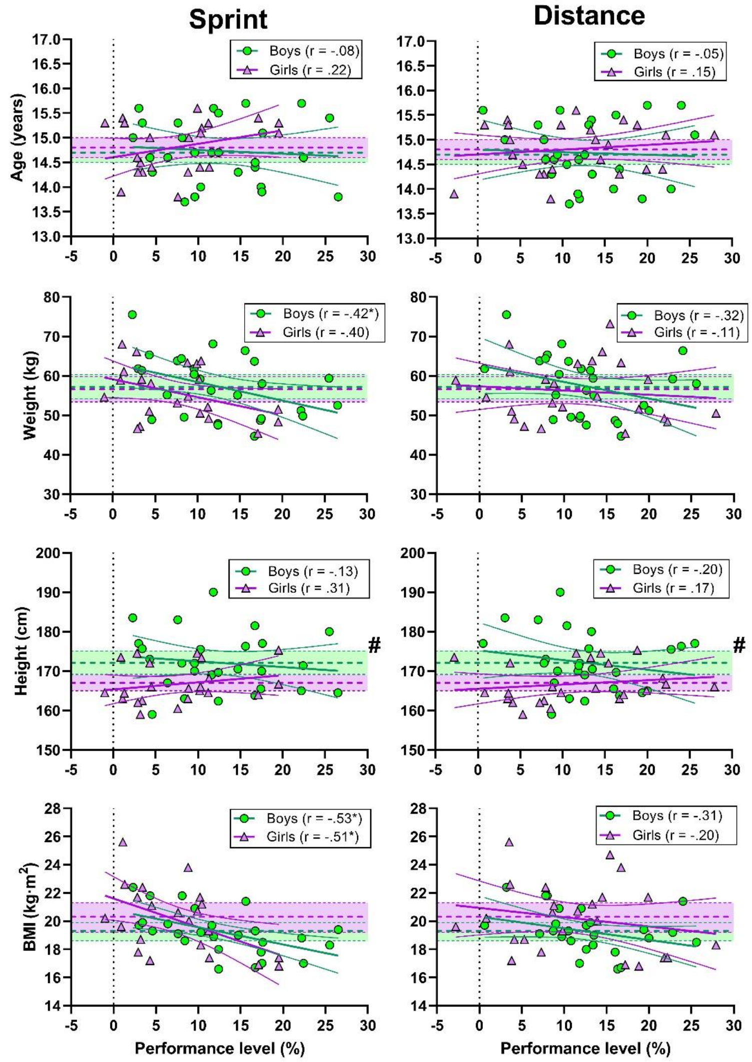
Correlation between indoor rollerski 3-min maximal uphill (8°) time-trial (TT_{3min}) performance and $\dot{V}O_{2peak}$, ΣO_{2def} and gross efficiency (GE). Green circles represent individual values for the boys. Purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green area for the boys and purple for the girls). Thick and narrow lines represent the best fit regression line and the 95% confidence bands (green lines for the boys and purple for the girls). * Correlation is significant at the .05 level. # significant difference between boys and girls.

Figure 4.



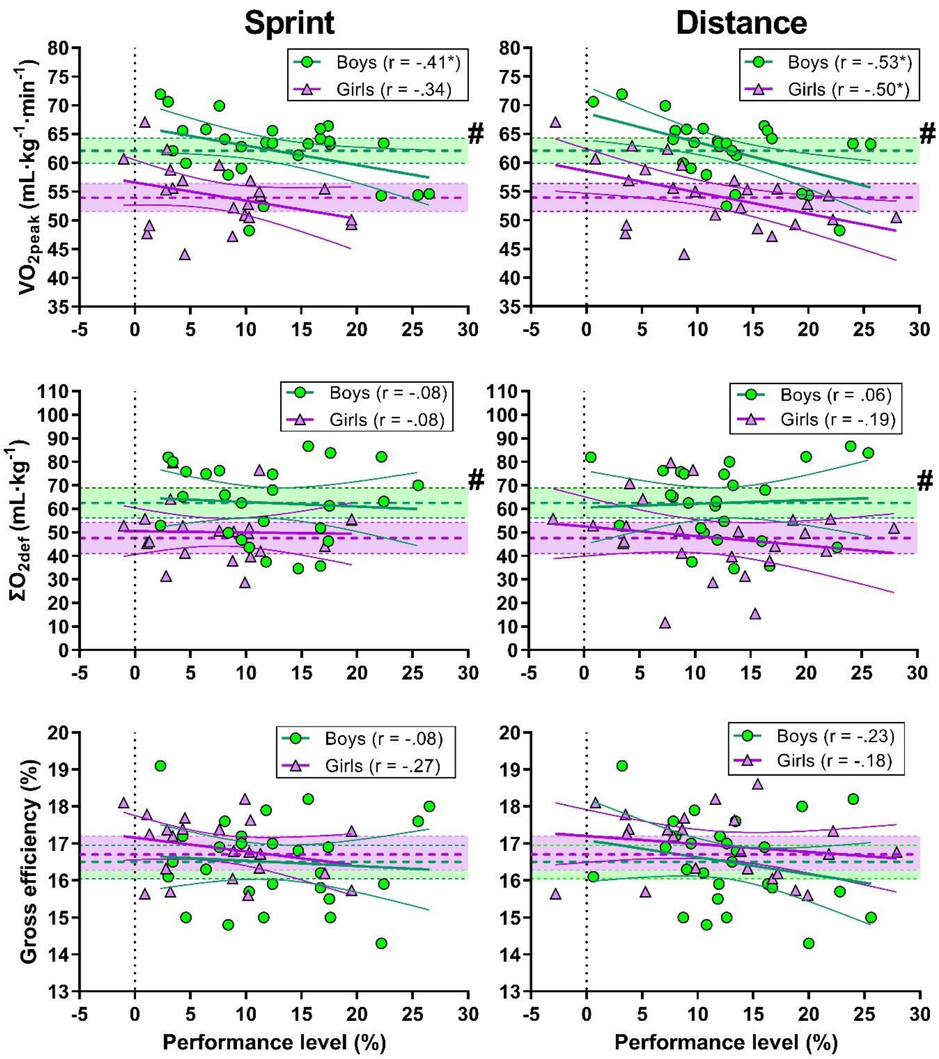
Correlation between indoor rollerski 3-min maximal uphill (8°) time-trial (TT_{3min}) performance and leg-press (upper panel) and pull-down (lower panel) strength. Green circles represent individual values for the boys. Purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green area for the boys and purple for the girls). Thick and narrow lines represent the best fit regression line and the 95% confidence bands (green lines for the boys and purple for the girls). * Correlation is significant at the .05 level. # significant difference between boys and girls.

Figure 5.



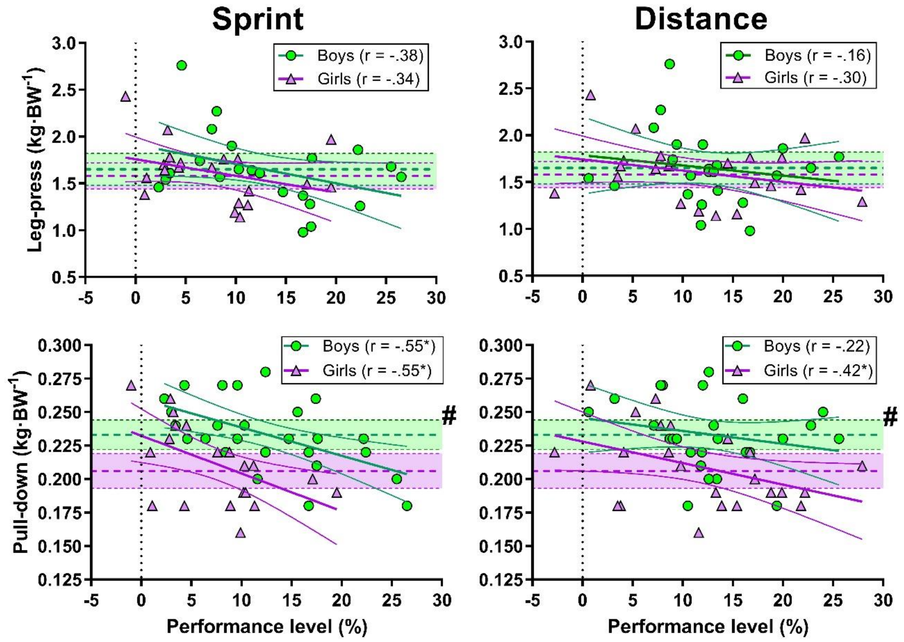
Correlation between sprint (left panel) and distance performance (right panel) and age, weight, height and BMI. Green circles represent individual values for the boys. Purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green area for the boys and purple for the girls). Thick and narrow lines represent the best fit regression line and the 95% confidence bands (green lines for the boys and purple for the girls). See method section for explanation of the performance level. * Correlation is significant at the .05 level. # significant difference between boys and girls.

Figure 6.



Correlation between sprint (left panel) and distance performance (right panel) and $\dot{V}O_{2peak}$, ΣO_{2def} and gross efficiency (GE). Green circles represent individual values for the boys. Purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green area for the boys and purple for the girls). Thick and narrow lines represent the best fit regression line and the 95% confidence bands (green lines for the boys and purple for the girls). See the method section for an explanation of the performance level. * Correlation is significant at the .05 level. # significant difference between boys and girls.

Figure 7.



Correlation between sprint (left panel) and distance performance (right panel) and leg-press (upper panel) and pull-down (lower panel) strength. Green circles represent individual values for the boys. Purple triangles represent individual values for the girls. Shaded areas with dotted lines in the middle represent mean ± 95% confidence interval (CI) (green area for the boys and purple for the girls). Thick and narrow lines represent the best fit regression line and the 95% confidence bands (green lines for the boys and purple for the girls). See the method section for an explanation of the performance level. * Correlation is significant at the .05 level. # significant difference between boys and girls.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

Both authors designed the study. OS performed the data collection and data analysis. Both authors drafted, edited and revised the manuscript. Both authors approved the final version of the manuscript.

Funding

This study was internally financed by the Department of Physical Performance at the Norwegian School of Sport Sciences.

Acknowledgments

Supplementary Material

Methods and results for comparing determinants of performance between top- and bottom-ranked tertiles from the TT_{3min} in the boys and girls.

Data Availability Statement

The datasets generated for this study are available on request from the corresponding author.

Paper II

Title

Sex differences in physiological determinants of performance within elite adolescent, junior and senior cross-country skiers.

Original investigation

Authors

Ove Sollie [1] and Thomas Losnegard [1]

[1] Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway

Corresponding author
Ove Sollie, Department of Physical Performance, Norwegian School of Sport Sciences
Sognsveien 220, PO Box 4014 Ulleval Stadion, 0806 Oslo, Norway.
Telephone: +47 23262311
Email: ove.sollie@nih.no

Running head: Age-group sex differences in XC skiing

Abstract word count: 239 words

Text-only word count: 3760 words

Number of figures and tables: 4

Abstract

Purpose: To compare sex differences in physiological determinants of skiing performance within elite adolescent, junior and senior cross-country skiers matched for performance level.

Methods: Eight male and twelve female adolescent (15±1 yrs), eight male and seven female junior (18±1 yrs), and seven male and six female senior (28±5 yrs) skiers participated. Gross efficiency (GE) was calculated during sub-maximal uphill treadmill roller skiing (~84% of $\dot{V}O_{2peak}$) using the G2 ski skating technique. $\dot{V}O_{2peak}$ and maximal accumulated oxygen deficit (ΣO_{2def}) were established from a 3-min time trial (TT_{3min}). 15-s maximal skiing power (P_{max}) was calculated from an incremental treadmill speed test. Finally, upper- and lower-body maximal strength tests were conducted.

Results: The TT_{3min} and P_{max} performance were 23% and 15% (adolescent), 24% and 19% (junior), and 17% and 14% (senior) greater for men than women (all groups, P≤.01, ES =2.43–4.18; very large). $\dot{V}O_{2peak}$ relative to body mass was 17% (adolescent, *P*=.002, ES=1.66, large), 21% (junior, *P*<.01, ES=2.60, very large), and 19% (senior, *P*<.01, ES=2.35, very large) greater for men than women. The within age-group sex difference in GE, relative ΣO_{2def} and strength were not significant, with the exception of greater lower-body strength in male compared to female juniors (*P*=.01, ES=1.26, large).

Conclusion: The very large within age-group sex difference in performance is of similar magnitude for adolescent, junior and senior skiers. This difference can likely be attributed to the large to very large sex difference in $\dot{V}O_{2peak}$ within all age-groups.

Keywords: Maximal oxygen uptake, gross efficiency, anaerobic capacity, cross-country skiing, strength

Introduction

The physical advantage of male compared to female athletes emerges during early adolescence, coinciding with the onset of male puberty (~12–13 yrs) [1]. This is driven by sex-specific changes in circulating levels of hormones, which in turn results in greater muscle mass, lower relative body fat and higher concentration of red blood cells and total red blood cell mass in men compared to women [2]. Throughout adolescence, the sex difference in endurance performance approaches the sex difference observed in senior athletes [3,4], which has been found to be approximately 8–12% [2].

In cross-country (XC) skiing, male athletes typically perform 10–12% better compared to their female counterparts [2,5] depending on the sub-technique employed, since the sex difference is magnified when the contribution from poling increases [6]. Olympic XC skiing lasts from ~3 min to 2 h in undulating terrain with varying speeds and thereby highly variable exercise intensities and complex interactions between energy system contributions [7]. Moreover, XC skiers frequently alternate between different sub-techniques with different requirements for upper- and lower-body propulsion. Therefore, the development of endurance and upper- and lower-body power is critical for successful skiers [8,9].

Maximal oxygen uptake [10-12], the ability to efficiently transform metabolic energy into speed (e.g., gross efficiency) [10,13] and the ability to repeatedly perform, and recover from, efforts above the maximal aerobic power [7] are key determinants for XC skiing performance. The increasing sex difference in maximal oxygen uptake relative to body weight during adolescence results in increased sex difference in running performance among adolescent XC skiers (12–15 yrs) [14]. Similar ski-specific results have also been observed in junior (~17–18 yrs) [15] and senior (~21–23 yrs) [5] skiers, and maximal oxygen uptake appears to be the primary determinant affecting the sex difference in XC skiing performance [2,16,17]. Similar skiing efficiency has been observed for senior male and female skiers [17] and only one study has calculated the sex difference in anaerobic capacity, finding no difference relative to body mass in junior skiers [15]. However, limited research exists regarding the sex difference in adolescent athletes, and no previous studies have explored sex differences for these variables in XC skiers within different age-groups.

Differences in muscular strength may affect anaerobic capacity via greater muscle mass [18] and greater upper-body power in men compared to women may partially explain sex differences in XC skiing performance [17,19]. However, the importance of strength appears to be technique-dependent since the different sub-techniques are characterized by varying contributions from upper- and lower-body propulsion [6], as well as the individual athlete´s ability to use their strength efficiently in the complex quadrupedal XC skiing techniques [20,21]. Furthermore, limited research exists on how the sex difference in strength affects skiing performance in adolescent and junior XC skiers.

Given the paucity of data relating to sex differences in adolescent XC skiers, our aim was to explore the sex difference in key physiological determinants of XC skiing performance within this age-group (~14–15 yrs). Further, we wanted to compare the sex difference in these elite adolescent skiers with the sex difference within elite junior (~18 yrs) and elite senior skiers (~28 yrs).

Methods

Participants

Participant characteristics are summarized in Table 1. Participants and the parents of those participants under the age of 18 were informed of the nature of the study and possible risks involved before giving their written consent. The study was approved by the Human Research Ethics Committee of The Norwegian School of Sport Sciences and registered with the Norwegian Centre for Research Data.

Performance level

Adolescent and junior skiers: Performance level was calculated as the percentage behind the mean time of the top three competitors during XC competitions for both adolescents and juniors (Table 1). For adolescents, performance level was calculated from the only national competition they have during the season ("Hovedlandsrennet", unofficial national championship). The skiers have the opportunity to compete in this race for two consecutive years (age 14 and 15 yrs) and, as such, performance level was calculated from the mean of these two races (five skiers had only one race included in the calculation). The adolescent skiers were also part of another study testing 54 skiers and, in order to match this sub-group for performance level, we included all skiers who were less than 10% behind the mean time of the top three skiers in "Hovedlandsrennet".

For junior skiers, performance level was calculated from their three best distance races in the Norwegian national cup in the closest season to testing. The junior skiers were recruited from local XC skiing clubs and matched for performance based on previous results in the national XC skiing cup. Four of the junior skiers (two male and two female) were part of the Norwegian junior national XC skiing team and had in total four medals from the FIS Junior World Ski Championships.

Senior: Performance level for the senior skiers was based on FIS points at the time of testing (Table 1) (FIS, 2019). These athletes were at a world-class performance level, and had won a total of 25 World Championship gold medals (men n = 3, women n = 3), seven Olympic gold medals (men n = 2, women n = 4), and had 115 individual world cup victories (men n = 5, women n = 4), at the end of 2018/2019 season. One world-class biathlete who had performed at an international level in XC skiing was also included in this group.

Testing

Testing was performed using the ski skating sub-technique G2 on a roller ski treadmill (Rodby, Sodertalje, Sweden) with dimensions of 3 × 4.5 m. To exclude possible variations in rolling resistance, all skiers used the same Swenor Skate roller skis (Sport Import AS, Sarpsborg, Norway) with wheel type 1 and a coefficient of friction of $\mu = 0.018$ and Rottefella binding systems (Rottefella AS, Lier, Norway) for all tests. The coefficient of friction was measured every week during the study period and was found to be consistent throughout. All participants used Swix Triac 1.0 and 3.0 poles of a self-selected length (~90% of body height) (Swix, Lillehammer, Norway), modified with a tip specifically adapted for use on a roller skiing treadmill. Participants were secured to the treadmill by a safety harness connected to an emergency brake during testing. Height, body mass and total mass including equipment were measured before each testing session (Seca model 877, Hamburg, Germany). $\dot{V}O_2$ was determined using a metabolic analyzer with mixing chamber (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany), calibrated according to the manufacturer’s instruction manual. Heart rate (HR) was measured throughout using a Polar M400 with a 1-Hz sampling rate (Kempele, Finland).

Familiarization

Prior to testing, the adolescent skiers completed two sessions to familiarize them with the apparatus and the different test protocols. The juniors were already accustomed to using the rollerskiing treadmill, and therefore only performed the second familiarization. The senior skiers had performed similar tests on numerous previous occasions and therefore performed only the main testing session due to time restrictions. The first familiarization consisted of 30 min submaximal roller ski skating, followed by two incremental speed tests (described below). The second familiarization session consisted of a 10-min self-paced warm-up and two 5-min sub-maximal G2 work bouts with cardiorespiratory measurements. The session ended with a familiarization to the strength testing protocol.

TT_{3min}

TT_{3min} was a 3-min maximal uphill time trial performed on the rollerski treadmill set to an 8° incline. The initial speed was 2.0 m·s^{-1} for the adolescent girls, 2.25 m·s^{-1} for the adolescent boys and junior women, 2.5 m·s^{-1} for the junior men and senior women, and 2.75 m·s^{-1} for the senior men. This speed was fixed during the first 30 s to prevent the skiers from going out too hard. Thereafter, the skiers themselves controlled the speed by adjusting their position on the treadmill relative to laser beams situated in front of and behind them. Each contact between the front or back wheels of the skis and the lasers induced a 0.25 m·s^{-1} increase or reduction in treadmill speed, respectively, conducted manually by the test leader. Visual feedback with respect to time was provided throughout. Cardiorespiratory variables ($\dot{V}O_2$ and RER) were monitored throughout the test and analyzed for $\dot{V}O_{2peak}$, defined as the average of the six highest consecutive 5-s measurements (total 30 s). The accumulated oxygen deficit (ΣO_{2def}) was determined by subtracting the accumulated $\dot{V}O_2$ from the accumulated estimated total $\dot{V}O_2$ requirements during the TT_{3min} [22]. Performance was defined as the total distance covered .

Main test session

Following a 6-min self-paced warm-up, participants completed 5-min submaximal rollerskiing at a 6° incline and a similar estimated relative intensity for all groups (83 ± 6 and 83 ± 4% of $\dot{V}O_{2peak}$ for the adolescents; 85 ± 6 and 86 ± 7% for the juniors; 80 ± 4 and 84 ± 4% for the seniors, for men and women respectively). The corresponding speed was 2.8 ± 0.2 and 2.3 ± 0.2 m·s^{-1} for the adolescents, 3.1 ± 0.2 and 2.5 ± 0.2 m·s^{-1} for the juniors and 3.5 ± 0.1 and 3.0 ± 0.1 m·s^{-1} for the seniors, for males and females respectively. Gross efficiency (GE) was calculated from this work bout as the work rate divided by the metabolic rate [22]. Cardiorespiratory variables and HR were monitored from 2–5 min and the average values used for further analysis. Rating of perceived exertion (RPE) (Borg Scale 6-20) [23], was recorded immediately upon cessation of exercise.

Incremental speed test

The test was performed 10 min after the sub-maximal test and was identical for all skiers. The test started at an incline of 8° and a speed of 2.5 m/s (estimated O_2-cost of ~66 ml·kg^{-1}·min^{-1}). The speed was increased by 0.25 m/s every 15 s (estimated increase of ~7 ml·kg^{-1}·min^{-1}). Participants skied between two laser beams projected on to the treadmill in front of and behind them. When they were no longer able to keep the front wheels of the skis ahead of the rear laser beam for two consecutive G2 technique cycles, the test was ended. Propulsive power on the treadmill was calculated as the sum of power against gravity and power against rolling resistance as previously described [10]. Maximal 15-s propulsive power (P_{max}) from the test relative to body mass was the performance outcome and was determined as:

Work rate last step completed + (Increase in work rate each step/time each step) x finished time final step.

Strength tests

One-repetition maximum (1RM) strength tests were performed 20 min after the end of the roller ski tests with the same protocol as described by Losnegard (2011) [24]. The order of the tests was the same for all skiers. Strength was tested separately for each arm and leg to determine whether there was a difference in strength between the right and left side. All 1RM testing was supervised by the same investigator and conducted using the same equipment, with identical equipment set-up for each skier.

Single leg press

Single leg press was performed on an inclined (45°) leg press machine. Before the test, the correct depth (90° knee angle) was measured and noted. The test started with straight legs before the skiers lowered the weights to the correct depth whereby they received a signal from the test leader to push back up. The attempt was considered valid when the weights were returned to the starting position.

Single arm pull-down

Seating was adjusted to a 90° angle at the knees and hips, with a “neutral” spine and back resting against a backboard with both feet flat on the floor throughout the test. The “non-testing arm” rested on the opposite thigh. The pull was performed holding a custom-made ski pole grip positioned at the height of the forehead. The wire was parallel to the back support. Participants then pulled the grip straight down, with the pull defined as valid when the hand hit the bench they were sitting on in one continuous motion, without bending the torso forward away from the backboard and with both feet kept on the ground.

Statistics

Normality of the data was assessed using the Shapiro-Wilks analysis ($\alpha = 0.05$) and visual inspection of Q-Q plots. For statistical tests, a level of $P \leq 0.05$ was considered significant. Raw data are presented as mean ± standard deviation (SD). Relative sex differences are presented as mean ± 95% confidence interval (CI). Independent samples *t* tests were used to compare within age-group sex differences. A one-way

ANOVA was conducted to investigate the relative sex differences between age-groups. The magnitudes of the differences between variables were expressed as standardized mean differences (Cohen's *d* effect size; ES). The criteria to interpret the magnitude of the ES were as follows: trivial 0.0–0.2; small 0.2–0.6; moderate 0.6–1.2; large 1.2–2.0; and very large >2.0 [25]. Statistical analyses were performed using GraphPad Prism 8 (GraphPad Software, San Diego, CA) and SPSS statistical package version 24 (SPSS Inc. Chicago, IL). In calculations of percent sex differences, the female XC skiers were treated as the reference data (100%).

Results

<<Table 1 around here>>

Performance tests

The distances achieved during TT_{3min} were 23%, 24% and 17% longer in male than female skiers for adolescent, junior and senior skiers respectively (all $P < .01$, all *ES* = very large (2.67–4.18), Fig. 1A). Male skiers achieved 15%, 19% and 14% higher P_{max} compared to their female counterparts in the adolescent, junior and senior groups respectively (all $P < .01$, all *ES* = very large (2.43–2.67), Fig. 1B).

Physiological determinants

During the TT_{3min}, the male skiers achieved a higher $\dot{V}O_{2peak}$ compared to their female counterparts (sex differences of 17%, 21% and 19% for adolescents, juniors and seniors respectively) (Fig. 1C and Table 1).

There were no significant sex differences in ΣO_{2def} relative to body mass during the TT_{3min}, but a moderate to large ES was found (Fig. 1D, P = .15–.27 and ES = .73, 1.48 and .70, adolescent, juniors and seniors respectively). The relative ΣO_{2def} accounted for 39 ± 8% and 40 ± 15% of the total energy contribution for the adolescents, 43 ± 7% and 44 ± 9% for the juniors and 36 ± 5% and 40 ± 6% for seniors, for all men and women, respectively. There were no differences in strength in any groups between the left and right arm or leg ($P > .05$ all groups). The strength values presented in this study are therefore the average of left and right sides. Both upper-body and lower-body strength relative to body mass were similar between men and women in all age-groups, except lower-body strength was higher in male juniors compared to female junior skiers (*P*=.01, *ES* =1.26) (Fig. 1E and 1F). Total strength was, however, significantly greater for the male compared to the female skiers in all age-groups (adolescents; 25% and 31%, juniors; 35% and 19%, seniors; 46% and 30% for lower- and upper-body strength respectively).

<<Figure 1 around here>>

During the sub-maximal work bout, the male skiers worked at a higher power output compared to their female counterparts (Fig 2B), but there was no significant sex difference for GE within the different age-groups (*P* = all <.25, ES = adolescents; small (.46), juniors; small (.29) and senior; moderate (.92), Fig. 2A).

At a similar relative exercise intensity, there was no sex difference in RPE with 15 ± 1 for the adolescent group (*P* = .91, ES = .09), 14 ± 1 for the junior group (*P* = .35, ES = .51) and 14 ± 1 for the senior group (*P* = .53, ES = .40).

<<Figure 2 around here>>

Overall sex differences

The percentage sex difference for the performance tests, VO_{2peak}, ΣO_{2def}, GE and strength within the respective age-groups are presented in Figure 3. The percentage sex differences were not different between age-groups (TT_{3min}: $F_{(2,20)}$ = 2.09, *P* = .15, P_{max}: $F_{(2,19)}$ = 1.36, *P* =.28, VO_{2peak}: $F_{(2,20)}$ = .60, *P* = .56, ΣO_{2def} : $F_{(2,18)}$ = .75, *P* = .49, GE: $F_{(2,19)}$ = 2.16, *P* =.14, Pull-down: $F_{(2,18)}$ = 1.97, *P* =.17, Leg press: $F_{(2,16)}$ = 1.75, *P* =.21.

<<Figure 3 around here>>

Discussion

The present study demonstrates that the sex difference in performance found in world-class senior XC skiers is of a similar magnitude for elite adolescent (~14–15 yrs) and junior (~18 yrs) skiers matched for performance within age-groups. The within age-group sex differences in key physiological determinants of performance were also similar between the age-groups.

The sex difference in performance for sprint and distance World Cup races the last 20 years has been found to be approximately 9–12% [26], similar to the 10–12% sex difference in performance observed in other endurance sports [2]. The sex difference of 14–24% in treadmill roller ski performance in the present study is greater, but is in accordance with previous studies investigating laboratory performance in junior and senior skiers [15,27]. This is likely related to the fact that during an on-snow competition, about ~25% of the time is spent in downhill sections where no propulsive power is required and the sex difference in speed thereby diminishes [28]. Furthermore, when skiing outdoors, the higher speed of male compared with female athletes is accompanied by a quadratic increase in air resistance [5].

In the present study, the overall sex difference (all age-groups combined) in performance for the TT_{3min} test (~24%) was larger than the overall sex difference in performance for the P_{max} test (~17%) ($P = .05$). The P_{max} test lasted ~1.3 min for the women when combining age-groups and ~2 min for the men. Consequently, the TT_{3min} test requires a relatively larger aerobic energy contribution compared to the P_{max} test (~70–75% vs ~55–65% [29]) and thereby favors skiers with a higher maximal aerobic power. The greater sex difference in performance for the TT_{3min} than the P_{max} may therefore be related to the 22% higher $\dot{V}O_{2peak}$ in men compared to women (age-groups combined). The sex difference in $\dot{V}O_{2peak}$ as an important contributor to the sex difference in endurance performance is supported by previous findings in other endurance sports [2] and in elite senior skiers matched for performance level [27]. The sex difference in $\dot{V}O_{2peak}$ in the present study was somewhat higher than the 10–15% difference previously found in other elite endurance athletes [16], but similar to other endurance sports with upper- and lower-body propulsive power such as rowing [30]. The reason for this difference is currently not known. It has been suggested that a larger upper-body muscle mass [2] and a more effective utilization of upper-body strength in men compared to women can explain some of the differences [6]. However, the ski-specific $\dot{V}O_{2peak}$ relative to running (e.g., $\dot{V}O_{2peak}$ in double poling vs. running) does not seem to be different between sexes or performance levels [26]. However, it should be noted that few studies have included female skiers in such comparisons and this aspect should be further investigated in future research.

Previously, a similar metabolic demand relative to $\dot{V}O_{2max}$ between elite male and female skiers has been found in outdoor race settings [5], showing a similar relative anaerobic contribution to total energy requirements between sexes in XC skiing, as supported by the present study. Moreover, we did not find a sex difference in relative strength or ΣO_{2def} in any groups. Similar relative strength is in contrast to a previous study of XC skiers [19], while similar relative ΣO_{2def} is supported by the only previous study in XC skiing calculating sex differences in anaerobic capacity [15]. However, the moderate to large effect size in the previous [15] and present study combined with a high typical error and CV for the calculation of ΣO_{2def} [26] may indicate that a real difference was not detected (Type 2 error).

Elite XC skiers are heavier than elite cyclists [31] and runners [32] indicating the need for well-developed upper- and lower-body power in XC skiing. Although strength relative to body mass was similar between sexes in the current study, the men were stronger independent of body mass and produced higher propulsive power compared to their female counterparts at a similar exercise intensity in all age-groups (Fig. 2B). This may affect the sex difference in outdoor XC skiing performance in flatter terrain. It has been proposed that increased strength in female skiers could increase performance [24], but this has not been supported by a previous strength training intervention [33]. Moreover, early studies investigating the effect of strength training on skiing performance proposed that strength training enhanced the skiing efficiency and thus performance [34,35]. However, the relationship between increased strength and increased efficiency has later been questioned, and female skiers do not appear to have a greater positive effect of strength training than male skiers [20,33]. Moreover, in the present study we did not find a difference in skiing efficiency between sexes within any age-groups, corresponding to previous findings in senior skiers [17]. As such, we question whether strength training should be differentiated between sexes, but perhaps rather individually tailored based on other factors.

Practical applications

Knowledge of what capacities are required for a specific sport is important for training optimization. The present study shows that when testing adolescent skiers (~14–15 yrs) coaches and testing staff may expect similar sex differences in physiological determinants of performance as found in older skiers.

Furthermore, our results demonstrate an overlap between sexes for individual values in the measured determinants where the best female skiers have higher values than the lowest ranked male skiers (Fig. 1 and 2). This may imply that training to enhance these variables should not necessarily be differentiated based on sex, but rather that coaches should focus on tailoring training programs to target areas of most need.

Methodological considerations

This study was part of a larger research project, with additional tests during the main test session to those described here. The adolescents and junior performed the TT_{3min} at the end of familiarization 2 while senior athletes performed all tests in a single day. Furthermore, breath-by-breath measures of $\dot{V}O_2$ were used for four male and seven female adolescent skiers and three male and two female junior skiers, while averaged measures (mixing chamber) were used for the remaining adolescent, junior and all senior skiers. This was due to a difference being found between breath-by-breath and mixing chamber measures during the research project [36]. However, since this study does not make comparisons between age-groups, this should not affect the conclusion. We present self-reported training volume in Table 1 to indicate approximate training volumes for each group, but these were not included in analyses due to uncertain validity. In addition, we did not perform predictive analysis due to the small sample size in the present study.

Conclusions

Sex differences in XC skiing performance ranged from ~15 to ~25% in lab-based performance tests within the different age-groups. These differences are already present in adolescent skiers (~14–15 yrs) and remains consistent through junior age (~18 yrs) and up to world-class senior performance level. The sex difference in performance can likely be attributed to the large to very large sex difference in $\dot{V}O_{2peak}$ within all age-groups.

References

1. Handelsman DJ. Sex differences in athletic performance emerge coinciding with the onset of male puberty. *Clin Endocrinol (Oxf).* 2017;87(1):68-72.
2. Sandbakk Ø, Solli GS, Holmberg HC. Sex Differences in World-Record Performance: The Influence of Sport Discipline and Competition Duration. *Int J Sports Physiol Perform.* 2018;13(1):2-8.
3. Senefeld JW, Clayburn AJ, Baker SE, Carter RE, Johnson PW, Joyner MJ. Sex differences in youth elite swimming. *Plos One.* 2019;14(11).
4. Cunningham LN. Physiologic comparison of adolescent female and male cross-country runners. *Pediatric Exercise Science.* 1990;2(4):313-321.

5. Andersson EP, Govus A, Shannon OM, McGawley K. Sex Differences in Performance and Pacing Strategies During Sprint Skiing. *Front Physiol.* 2019;10:295.
6. Sandbakk Ø, Ettema G, Holmberg HC. Gender differences in endurance performance by elite cross-country skiers are influenced by the contribution from poling. *Scand J Med Sci Sports.* 2014;24(1):28-33.
7. Sollie O, Gløersen Ø, Gilgien M, Losnegard T. Differences in pacing pattern and sub-technique selection between young and adult competitive cross-country skiers. *Scand J Med Sci Sports.* 2020.
8. Børve J, Jevne SN, Rud B, Losnegard T. Upper-Body Muscular Endurance Training Improves Performance Following 50 min of Double Poling in Well-Trained Cross-Country Skiers. *Front Physiol.* 2017;8:690.
9. Talsnes RK, van den Tillaar R, Cai X, Sandbakk Ø. Comparison of High- vs. Low-Responders Following a 6-Month XC Ski-Specific Training Period: A Multidisciplinary Approach. *Front Sports Act Living.* 2020;2:114.
10. Losnegard T, Myklebust H, Spencer M, Hallen J. Seasonal variations in VO2max, O2-cost, O2-deficit, and performance in elite cross-country skiers. *J Strength Cond Res.* 2013;27(7):1780-1790.
11. Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G. The physiology of world-class sprint skiers. *Scand J Med Sci Sports.* 2011;21(6):e9-16.
12. Sandbakk Ø, Hegge AM, Losnegard T, Skattebo O, Tønnessen E, Holmberg HC. The Physiological Capacity of the World's Highest Ranked Female Cross-country Skiers. *Med Sci Sports Exerc.* 2016;48(6):1091-1100.
13. Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G. Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *Eur J Appl Physiol.* 2010;109(3):473-481.
14. Landgraff HW. Cardiorespiratory, hematological and body composition changes in maturing girls and boys with different training backgrounds. In:2020.
15. McGawley K, Holmberg HC. Aerobic and Anaerobic Contributions to Energy Production Among Junior Male and Female Cross-Country Skiers During Diagonal Skiing. *Int J Sport Physiol.* 2014;9(1):32-40.
16. Joyner MJ. Physiological limits to endurance exercise performance: influence of sex. *J Physiol.* 2017;595(9):2949-2954.
17. Hegge AM, Bucher E, Ettema G, Faude O, Holmberg HC, Sandbakk Ø. Gender differences in power production, energetic capacity and efficiency of elite crosscountry skiers during wholebody, upperbody, and arm poling. *Eur J Appl Physiol.* 2016;116(2):291-300.

18. Perez-Gomez J, Rodriguez GV, Ara I, et al. Role of muscle mass on sprint performance: gender differences? *Eur J Appl Physiol.* 2008;102(6):685-694.
19. Hegge AM, Myhre K, Welde B, Holmberg HC, Sandbakk Ø. Are gender differences in upper-body power generated by elite cross-country skiers augmented by increasing the intensity of exercise? *Plos One.* 2015;10(5):e0127509.
20. Losnegard T. Strength Training for Cross-Country Skiers. In: Schumann M, Rønnestad BR, eds. *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications.* Cham: Springer International Publishing; 2019:357-368.
21. Stöggl T, Müller E, Ainegren M, Holmberg HC. General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand J Med Sci Sports.* 2011;21(6):791-803.
22. Andersson EP, McGawley K. A Comparison between Different Methods of Estimating Anaerobic Energy Production. *Front Physiol.* 2018;9:82.
23. Borg G. *Physical performance and perceived exertion* [Dissertation]. Lund, Lund.; 1962.
24. Losnegard T, Mikkelsen K, Rønnestad BR, Hallen J, Rud B, Raastad T. The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. *Scand J Med Sci Sports.* 2011;21(3):389-401.
25. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc.* 2009;41(1):3-13.
26. Losnegard T. Energy system contribution during competitive cross-country skiing. *Eur J Appl Physiol.* 2019;119(8):1675-1690.
27. Sandbakk Ø, Ettema G, Leirdal S, Holmberg HC. Gender differences in the physiological responses and kinematic behaviour of elite sprint cross-country skiers. *Eur J Appl Physiol.* 2012;112(3):1087-1094.
28. Bolger CM, Kocbach J, Hegge AM, Sandbakk Ø. Speed and heart-rate profiles in skating and classical cross-country skiing competitions. *Int J Sports Physiol Perform.* 2015;10(7):873-880.
29. Gastin PB. Energy system interaction and relative contribution during maximal exercise. *Sports Med.* 2001;31(10):725-741.
30. Yoshiga CC, Higuchi M. Rowing performance of female and male rowers. *Scand J Med Sci Sports.* 2003;13(5):317-321.
31. Impellizzeri FM, Marcora SM. The physiology of mountain biking. *Sports Med.* 2007;37(1):59-71.
32. Daniels J, Daniels N. Running economy of elite male and elite female runners. *Med Sci Sports Exerc.* 1992;24(4):483-489.
33. Skattebo Ø, Hallen J, Rønnestad BR, Losnegard T. Upper body heavy strength training does not affect performance in

junior female cross-country skiers. *Scand J Med Sci Sports.* 2016;26(9):1007-1016.
34. Østeras H, Helgerud J, Hoff J. Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *Eur J Appl Physiol.* 2002;88(3):255-263.
35. Hoff J, Helgerud J, Wisløff U. Maximal strength training improves work economy in trained female cross-country skiers. *Med Sci Sports Exerc.* 1999;31(6):870-877.
36. Gløersen Ø, Gilgien M, Dysthe DK, Malthe-Sørenssen A, Losnegard T. Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med Sci Sports Exerc.* 2020;52(4):983-992.

Figure legends

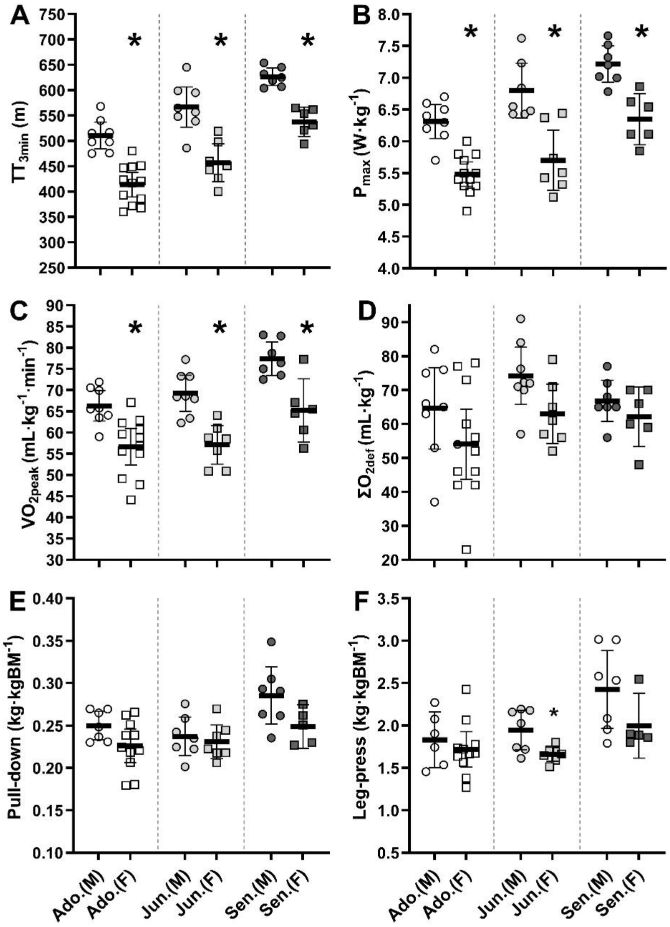


Figure 1. Measurements from the maximal tests. A) Distance covered (m) during the TT_{3min}; B) P_{max}, highest 15-s power during the incremental speed test; C) relative $\dot{V}O_{2peak}$; D) relative ΣO_{2def} from TT_{3min}; E) single-arm pull-down and F) single leg-press weight relative to body mass. Data are presented as mean ± 95% CI. * significantly lower compared to male counterparts ($P < .05$). kgBM = kg body mass, TT_{3min} = 3-min maximal time trial. Ado.; adolescent skiers, Jun.; junior skiers, Sen.; senior skiers, (M); Male, (F); Female.

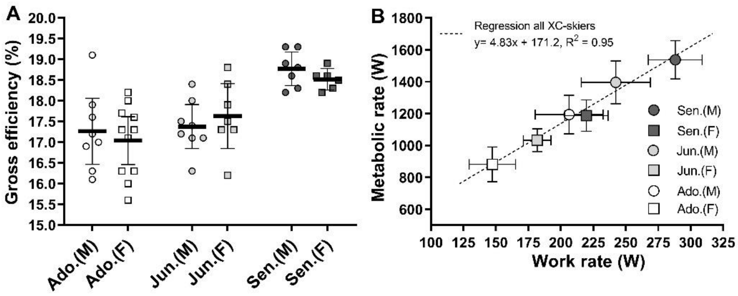


Figure 2. Measurements from the submaximal work bout. A) Gross efficiency (%) for the different groups with individual data. Data are presented as mean ± 95% CI. B) Submaximal metabolic rates in relation to work rates. Data are presented as mean ± SD. Ado.; adolescent skiers, Jun.; junior skiers, Sen.; senior skiers, (M); Male, (F); Female.

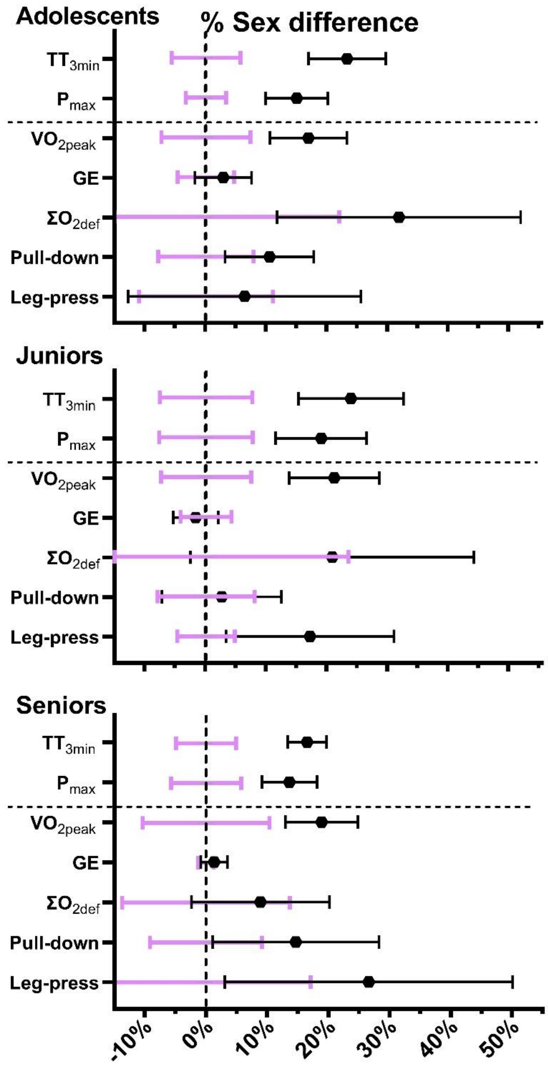


Figure 3: Visualization of the percentage difference between male and female XC skiers for roller ski performance, $\dot{V}O_{2peak}$, GE, ΣO_{2def}, pull-down and leg-press strength in the different age-groups. The black symbols and black error bars represent mean ± 95% CI for the male skiers as percentages compared to the mean of the female skiers (defined as 100%) in the same age-group (black dotted line at 0%). Purple error bars represent ± 95% CI in percentages around the mean of the female skiers. Negative error bars below -15% are cut for visualization purposes. TT_{3min} = 3-min maximal time trial, P_{max} = highest 15-s power output during the incremental speed test, ΣO_{2def} = accumulated oxygen deficit during the TT_{3min}, GE = Gross Efficiency, Pull-down = Single arm pull-down, Leg-press = Single leg press.

Tables

Table 1. Participant characteristics in performance level, anthropometrics, $\dot{V}O_{2peak}$ in the G2 ski skating technique and total training volume for male and female XC skiers in the different age-groups. Data are displayed as mean ± SD. The age of the adolescents was calculated from time of birth to the time of testing, while the age of juniors and seniors are shown in whole years.

Adolescents	**Male (n=8)**	**Female (n=12)**	***P*-value**	**Effect size**
[1]*Performance level (%)*	9 ± 3	7 ± 4	.29	Small (.50)
Age (years)	15.0 ± 0.4	14.7 ± 0.6	.15	Small (.56)
Body mass (kg)	64.3 ± 5.9	54.9 ± 6.1	<.01	Large (1.56)
Body height (cm)	177 ± 8	165 ± 4	<.01	Very Large (2.04)
Body Mass Index ($kg \cdot m^{2}$)	20.5 ± 1.4	20.3 ± 2.3	.80	Trivial (.10)
VO_{2peak} ($mL \cdot kg^{-1} \cdot min^{-1}$)	66.3 ± 4.3	56.7 ± 6.5	<.01	Large (1.67)
Total training ($h \cdot week^{-1}$)	12.8 ± 3.4	9.7 ± 2.6	.04	Moderate (1.06)
Junior	**Male (n=8)**	**Female (n=7)**	***P*-value**	**ES**
[1]*Performance level (%)*	7 ± 7	9 ± 7	.67	Small (.24)
Age (years)	18 ± 1	18 ± 1	.87	Trivial (.01)
Body mass (kg)	69.7 ± 5.8	61.1 ± 6.1	.01	Large (1.45)
Body height (cm)	181 ± 5	168 ± 5	<.01	Very Large (2.51)
Body Mass Index ($kg \cdot m^{2}$)	21.3 ± 1.1	21.7 ± 1.8	.65	Small (.27)
VO_{2peak} ($mL \cdot kg^{-1} \cdot min^{-1}$)	69.3 ± 4.8	57.1 ± 4.6	<.01	Very Large (2.59)
Total training ($h \cdot week^{-1}$)	11.7 ± 2.0	10.6 ± 1.2	.28	Moderate (.67)
Senior	**Male (n=7)**	**Female (n=6)**	***P*-value**	**ES**
[1]*Performance level (FIS)*	16 ± 15	19 ± 18	.69	Small (.26)
Age (years)	28 ± 5	28 ± 3	.99	Trivial (.02)
Body mass (kg)	73.8 ± 6.2	63.4 ± 5.8	.02	Moderate (.97)
Body height (cm)	178 ± 5	170 ± 5	<.01	Moderate (1.59)
Body Mass Index ($kg \cdot m^{2}$)	23.3 ± 1.0	21.8 ± 1.0	.03	Moderate (1.40)
VO_{2peak} ($mL \cdot kg^{-1} \cdot min^{-1}$)	77.5 ± 3.9	65.2 ± 6.5	<.01	Very Large (2.35)
Total training ($h \cdot week^{-1}$)	18.6 ± 1.7	16.5 ± 1.9	.77	Trivial (.15)

[1] See method section for details regarding calculations of performance level for the different groups.

Declarations

Funding: This study was internally financed by the Department of Physical Performance at the Norwegian School of Sport Sciences.

Conflicts of interest: There are no conflicts of interest, including financial, consultant, institutional, or other relationships that might lead to bias or conflict of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation

Availability of data and material: The datasets generated for this study are available on request from the corresponding author.

Authors' contributions: OS and TL designed the study. OS and TL performed the data collection. Data analysis was performed by OS. OS and TL drafted, edited and revised the manuscript. OS and TL approved the final version of the manuscript.

Paper III

Received: 26 July 2020 | Revised: 21 September 2020 | Accepted: 5 November 2020
DOI: 10.1111/sms.13887

ORIGINAL ARTICLE

WILEY

Differences in pacing pattern and sub-technique selection between young and adult competitive cross-country skiers

Ove Sollie[1] | Øyvind Gløersen[1] | Matthias Gilgien[1,2] | Thomas Losnegard[1]

[1]Department of Physical Performance, Norwegian School of Sports Sciences, Oslo, Norway
[2]St. Moritz Health and Innovation Foundation, Samedan, Switzerland

Correspondence
Ove Sollie, Department of Physical Performance, Norwegian School of Sport Sciences, Sognsveien 220, PO Box 4014 Ullevål Stadion, 0806 Oslo, Norway.
Email: ove.sollie@nih.no

The present study describes differences in pacing patterns and sub-technique selection in young compared to adult competitive cross-country skiers. Eleven young male skiers (YOS) (14.4 ± 0.5 years, $\dot{V}O_{2peak}$ 63.9 ± 2.8 mL•kg^{-1}•min^{-1}) and eight adult male skiers (ADS) (22.6 ± 4.3 years, $\dot{V}O_{2peak}$ 77.4 ± 4.4 mL•kg^{-1}•min^{-1}) performed a free technique rollerski time trial (TT) over a distance of 4.3 km (YOS) and 13.1 km (ADS) to simulate normal racing distances. A GNSS/IMU system was used to track position, speed, and classify sub-techniques. Skiing economy and $\dot{V}O_{2peak}$ were measured on an additional day to calculate the relative oxygen demand ($\dot{V}O_{2dem}$) in 13 segments of the TT. YOS were slower than ADS in all types of terrain (mean speed difference of 13%), with differences for uphills of 19%, undulating terrain of 11% and downhills of 8% (all $P < .05$). The mean relative $\dot{V}O_{2dem}$ tended to be higher for YOS compared to ADS (120% vs 112% of $\dot{V}O_{2peak}$, $P = .09$), and the difference was more pronounced in the initial four segments of the race (130% vs 110% of $\dot{V}O_{2peak}$, $P < .01$). YOS used more of the sub-technique Gear 2 (23 ± 7 vs 14 ± 4%), less Gear 3 (36 ± 7 vs 45 ± 5%), and had more frequent transitions between sub-techniques (18 ± 2 vs 15 ± 3 km^{-1}) (all $P < .05$) than ADS. Over an age-related distance, young skiers tend to exhibit higher mean exercise intensity than adult elite skiers, with a more pronounced positive pacing pattern. Differences in physical ability affect speed and sub-technique selections, implying a need for differentiating technical training for different ages and levels.

KEYWORDS
adolescents, exercise intensity, metabolic demand, performance, power output, race strategy, talent development, time trial

1 | INTRODUCTION

Competitive cross-country skiing (XC-skiing) involves complex whole-body movements where the goal is to complete a known course in the shortest time possible. During a race, skiers face large fluctuations in speeds, imposed by the topography of the course, which induce varying exercise intensities and repeated transitions between sub-techniques.[1-4] Accordingly, successful skiing performance depends strongly on the skiers' pacing strategy; that is, their ability to decide how and when to invest their energy resources during the race.[5,6]

XC-skiers normally apply a positive pacing strategy on a lap-to-lap basis irrespective of distance, technique, or sex, with a typical decrease in speed of 2%-12% during competitions.[7] Within laps, recent studies demonstrate that skiers also perform a variable pacing pattern due to the undulating terrain.[1,4] Here, adult elite skiers work at an intensity well above their maximal aerobic power in the uphills, close to their maximal aerobic power in flat terrain and below it during downhills.[1,4] The ability to rapidly recover from these supramaximal workloads seems to be a key requisite for successful XC-skiing. However, as adult elite athletes have a more developed aerobic endurance and anaerobic capacity than young athletes,[8,9] it is not clear whether young skiers have similar abilities to repeatedly perform, and recover from, efforts above their maximal aerobic power, and thereby induce similar relative exercise intensities to those observed in adult skiers.

Maturation and experience play a major role in optimizing pacing strategies,[10,11] and hence, the learning process for pacing optimization can be of great importance in the development and future performance of young athletes.[12] Adding to the complexity of pacing in XC-skiing, accessible tools to monitor exercise intensity, such as heart rate monitors, do not reflect the rapid fluctuations in exercise intensity during races.[1,13,14] Therefore, these tools are not suitable to help young athletes to improve their pacing, and acquisition of pacing skills is therefore subject to a trial and error type of learning. Evidently, as level of expertise affects pacing, better skiers seem to maintain their speed to a greater extent compared to slower skiers throughout distance time trials (TTs).[6,15] In addition, older and thereby more experienced skiers seem to distribute their effort in a manner that allows better performance compared to less experienced skiers with the same physiological capabilities.[16-18] However, to date, no study has provided experimental data to assess differences in pacing for different age groups in XC-skiing.

Competitive XC-skiing consists of two separate techniques (classic style and free style; called skating) each with several sub-techniques. The sub-techniques act as a gearing system where the speed is the main factor affecting the choice of gears.[19] Therefore, faster skiers demonstrate more use of "high-speed gears" compared to slower skiers during competitions.[14,15] Given the large fluctuations in speed during a race, elite skiers normally perform about 15-25 transitions between sub-techniques or "gears" per km[2,3,20] and efficient transitions between gears may improve finishing times.[2] Thus, gear selection is an important part of pacing and is probably related to the performance level and may vary with age groups and experience. Although several studies have investigated gear selection in relation to terrain and athletes,[2,3,14] no studies have included young skiers. Furthermore, no studies have used the combination of GNSS and IMU technology to describe gear selection in skating during a race. Describing age-specific gear selections for young skiers may provide important information for coaches and athletes seeking to optimize performance development in young athletes.

Given the importance of pacing for performance and the paucity of data relating to young skiers, the aim of the current study was to investigate differences in pacing patterns, and thereby exercise intensity and gear selection, between adolescent and adult XC-skiers. We hypothesized that both groups would apply a variable pacing pattern, with a more pronounced positive pacing pattern for the young skiers. Furthermore, the lower speeds applied by the young skiers would induce more use of lower gears compared to the adults.

2 | MATERIAL AND METHODS

2.1 | Participants

Eleven young male competitive skiers (YOS) (14.4 ± 0.5 years; 58.9 ± 7.3 kg; $\dot{V}O_{2peak}$ 63.9 ± 2.8 mL•kg^{-1}•min^{-1}) and eight adult male competitive skiers (ADS) (22.6 ± 4.3 years; 77.1 ± 5.3 kg; $\dot{V}O_{2peak}$ 77.4 ± 4.4 mL•kg^{-1}•min^{-1}) participated in the study. ADS had an FIS point range of 13-117 (Norwegian national rank 9-278), while YOS placed between 20th and 167th in ~ 300 participants in the Norwegian unofficial national championship ("Hovedlandsrennet") in their respective age groups, four months after testing. All skiers gave their informed written consent to participate in the study. Written parental consent was obtained for skiers younger than 18 years. The study was approved by the ethics committee at the Norwegian School of Sport Sciences, found advisable by the Norwegian Centre for Research Data, and conducted according to the Declaration of Helsinki.

2.2 | Experimental overview

The skiers completed two (ADS) or three (YOS) test sessions during the fall, separated by 16.8 ± 6.3 days. The first session consisted of an individual free technique roller ski TT performed on the same international racecourse for both groups. ADS raced 13.1 km (2 × 4.4 km + 4.3 km) and YOS raced 4.3 km to simulate normal age-related racing distances the two groups are used to perform in real competitions. The reason for the discrepancy in lap lengths between groups was due to the ~100 m extra distance when starting a new lap. Throughout the TT, position and speed were measured using a standalone GNSS receiver mounted on the skier. The second session was a laboratory session on a roller skiing treadmill where the individual cost of transport (*C*) during sub-maximal loads for different speeds and inclinations was assessed for both groups. $\dot{V}O_{2peak}$ and maximal accumulated oxygen deficit (MAOD) were measured after the sub-maximal loads for ADS, while this was performed in a separate session for YOS. Individual exercise intensity, expressed as

$\dot{V}O_{2dem}$, was calculated for different segments of the course, assuming a linear relationship between *C* and the propulsive force (F_{prop}).[4] F_{prop} was calculated from the standalone GNSS receiver position measurements collected during the TT, combined with a model for air drag and differential carrier-phase GNSS measurements of the ski course. Classification of each skier's gear selection throughout the TT was achieved by visual inspection of gyroscope and accelerometer signals from an inertial measurement unit (IMU) mounted on the skier, in combination with the position and speed of the skier on the course.

2.3 | Instruments and materials

A 10 Hz standalone GNSS receiver (Catapult Optimeye S5, mass 67 g, firmware version 7.18, Melbourne, Australia) with a 9-axis IMU (accelerometer, gyroscope and magnetic field measurements) was used for position and speed tracking, for F_{prop} calculations, and for inspection of accelerometer and gyroscope signals for gear classification during the TT. Methodological details can be found in Gløersen et al (2018).[21]

Laboratory tests were performed on a roller skiing treadmill with belt dimensions 3 × 4.5 m (Rodby, Södertälje, Sweden). All athletes used roller skis (Swenor, Sarpsborg, Norway) they were accustomed to (ADS: Swenor Skate Long, length 630 mm, weight 795 g•ski^{-1}; YOS: Swenor Skate; length 580 mm, weight 705 g•ski^{-1}). All skiers used the same wheel type with the same coefficient of rolling resistance (C_{rr}) (Swenor, wheel type 2, Swenor Skate Long 0.0225 ± 0.0009; Swenor Skate 0.0215 ± 0.0004) in all tests, except during the TT_{1000m} and the TT_{3min} for ADS and YOS, respectively, where wheel type 1 with lower C_{rr} was used (see methodological considerations). Each athlete used the same pair of roller skis on both testing days. The C_{rr} for each pair of roller skis used during both tests was measured prior to the study using a towing test on the roller skiing treadmill as described previously.[22] Athletes used their own ski poles on the TT, and Swix Triac 3.0 ski poles (Swix Sports, Lillehammer, Norway) of equal lengths with customized ferrules during the laboratory testing.

Oxygen consumption was measured using an automatic ergospirometry system (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany). The Oxycon Pro Jaeger Instrument was calibrated according to the instruction manual as described in detail previously.[23] Breath-by-breath measurements were used for ADS, while mixing chamber mode was used for YOS (see methodological considerations). Blood samples were taken from a fingertip after each 5-min bout and were analyzed for the determination of blood lactate concentration (Biosen C-line, EKF diagnostic GmbH, Magdeburg, Germany). The Biosen system was calibrated with a standard solution of lactate (12 mmol L^{-1}) prior to the analysis. Body mass and total mass including equipment were measured before each testing sessions (Seca model 877, Hamburg, Germany). Heart rate was recorded with the same heart rate monitor on both test days, measuring at 1 Hz (Polar M400, Kempele, Finland). Rating of perceived exertion (RPE) was evaluated using the Borg scale (6-20)[24] directly after each 5-min steady-state load.

2.4 | Day 1. Time Trial

The TT was conducted in Holmenkollen, Oslo, Norway, with similar topography to the racecourse used during winter competitions (distance 4.3 km, height difference 51 m, maximum climb 32 m, total climb 166 m). The procedure is described in detail in a previous study[21] but is summarized here for clarity. Before the warm-up, the weight of the athletes including equipment (including roller skies, ski poles, ski boots, and helmet) was measured.

2.4.1 | Warm-up

Both groups were instructed to complete one lap at an easy pace, before they were given 10 min to warm up as they normally would do before a regular competition.

2.4.2 | Time Trial

To simulate normal TT distances for the two groups, ADS were instructed to complete three laps (13.1 km) and YOS one lap (4.3 km) as fast as possible. No other instructions regarding pacing strategy were given. The skiers started at 2-min intervals in ranked order to minimize overtaking and possibly drafting. The asphalt was dry on all test occasions, and the athletes wore tight-fitting clothes during the race. Each skier was equipped with a Catapult S5 unit, which was used for position and speed calculations, and gear classification. The TT terrain was described according to FIS's official homologation manual which defines different segments: A, B, and C climbs (no C climbs on this course), undulating terrain (UT) and downhills (D) (Figure 1) (A-climb = Major uphills, partial height difference (PHD) ≥ 30 m. B-climbs = Short uphills, 10 m ≤ PHD ≤29 m, incline 9% - 18%. UT = combination of flat and rolling terrain including short climbs, flat sections, and downhills). See the official manual for further details.[25] A trajectory through the TT course was measured before the data collection, using a highly accurate dual-frequency differential carrier-phase GNSS,[26] and the different segments were defined based on the incline calculation of this trajectory. $\dot{V}O_{2dem}$ and propulsive power (P_{prop}) were

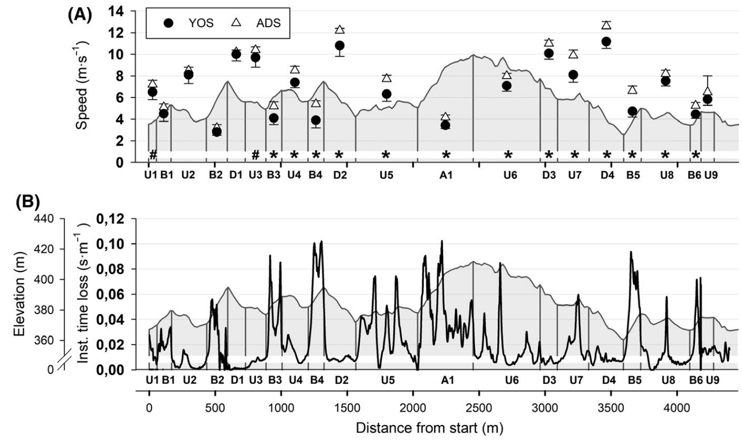


FIGURE 1 Mean segment speed and instantaneous time loss for YOS compared to ADS throughout the TT. A) Mean speed for the different segments. The segment calculations for the ADS are averaged for the three laps. B) Instantaneous time loss (Seconds per meter) for YOS compared to ADS throughout the TT. Mean segment speed (A) is presented as mean ± SD. * significant between-group differences ($P < .05$) and, # tendency for between-group differences ($P < .10$). The altitude profile of the racetrack used during the TT is shown behind the data points. Segments are separated by drop lines. The altitude profile in A is the same as B without units

calculated by combining measurements from the Catapult S5 unit with the trajectory of the course measured by the differential GNSS.[4,21] U9 on the last lap for ADS was not analyzed by Gløersen (2019) and is also omitted here for ADS on the last lap. Heart rate data were collected throughout the TT with an HR monitor. Environmental temperature, air pressure, and wind data were retrieved from local weather stations (met.eklima.no, Meteorological Institute of Norway, Oslo, Norway).

2.5 | Gear classification

Inertial and position data were retrieved from the Catapult S5 unit, which was mounted on the skiers during the TT. The manufacturer's software (Catapult Sprint, version 5.14; Catapult Sports) and a custom-made MATLAB application developed specifically for visual inspection of these measurements were used in combination for gear classification. Classification was based on visual inspection of the gyroscope and accelerometer signals, in combination with the position and speed of the skier on the course. Gear classification was performed throughout the TT for YOS and the first lap for ADS. The classification was performed by an experienced XC-skiing coach familiar with the racecourse and the equipment/software used. Gears were defined as previously suggested with three main gears ranging from G2 used at low speed uphill up to G4 used at high speed in mostly flat terrain.[19] Additionally, miscellaneous (misc.) is defined in this case as both skating without poles and active turning technique. Lastly, tucked position (TP) is defined as a downhill technique where the skiers are not generating propulsive force. The manual classification method was validated using recordings of two elite skiers who performed a TT around the same course with the same Catapult S5 unit mounted in the same way, with cameras mounted to detect the different gears. The gear classification of these two skiers was then visually inspected using the gyroscope and accelerometer signals, in combination with the position and speed of the skiers on the course, before validated against the video. The intra-rater reliability for the combined micro-sensor and video classification was high (ICC = 0.95 (95% CL = 0.8-0.99).

2.6 | Day 2: Laboratory tests

Both groups performed tests for C, $\dot{V}O_{2peak,}$ and MAOD. Since the groups were also included in other projects, the methods for C, $\dot{V}O_{2peak,}$ and MAOD were slightly different between the groups. This is further discussed under "methodological considerations."

2.6.1 | ADS

Skiing C was calculated from six different loads, each of 5 min, with varying treadmill speeds and inclinations as described in detail in Gløersen et al (2020).[4] $\dot{V}O_{2peak}$ and MAOD were calculated from a self-paced 1000 m test (TT_{1000m}, duration ~ 4 min) at 6° inclination using G3.[27] $\dot{V}O_{2peak}$ was defined as the highest 60 s running average during the TT_{1000}.

2.6.2 | YOS

C was calculated from six different loads, each of 5 min, while measuring $\dot{V}O_2$, where speed was adjusted to correspond to a range in intensity of 60%-80% of $\dot{V}O_{2peak}$. $\dot{V}O_{2peak}$ and MAOD were calculated from a 3-min all-out TT (TT_{3min}) at 8° inclination using G2. This test was performed prior to the calculation of C on a separate day. The speed during TT_{3min} was held constant for the first 30 s at 2.25 m·s^{-1} before the skiers self-paced and performed the rest of the test in the same manner as the TT_{1000m} for ADS. $\dot{V}O_{2peak}$ was defined as the highest rate of oxygen consumption averaged from the six highest consecutive 5-s measurements (total 30 s) from TT_{3min}.

For both groups, MAOD was calculated as the difference between accumulated oxygen demand and accumulated oxygen consumption over the complete TT_{1000m} or TT_{3min}.[28] The reliability coefficient (typical error expressed as CV) for the TT_{1000m} and TT_{3min} has been shown to be 2.5 and 2.4%, respectively.

2.7 | Propulsive power

P_{prop} on the treadmill was calculated as the sum of power against gravity (P_g) and power against rolling resistance (P_{rr}) as previously described.[27] During the TT, P_{prop} was calculated for sections of the course where the skiers continuously generated active propulsion. Sections with calculated P_{prop} are categorized under the same name as the segment name (Figure 2—dark gray area). P_{prop} was not calculated where athletes used the tucked position (Figure 2—light gray area). This calculation also accounted for air drag [1] and changes in kinetic energy.[21] Specifically, the following equation was used to calculate P_{prop} (Equation 1):

$$P_{prop} = \frac{\left(\Delta E_{mech} + W_{env}\right)}{t}$$
$$= \frac{\left(m\left(\frac{1}{2}\left(v_{out}^2 - v_{in}^2\right) + g\Delta z\right) + d\left(\frac{1}{2}\rho C_D A \overline{v}^2 + C_{rr} m g \overline{\cos\theta}\right)\right)}{t}$$
#

In equation 1, m is the mass of the athlete and equipment; v_{in} and v_{out} are the skiing speeds at the entry and exit of each segment, respectively; $g = 9.81$ m•s^{-2} is the acceleration due to gravity; Δz is the change in vertical position during the segment; d is the length of the segment; ρ is the air's density; $C_D A$ is the drag area of the skier, C_{rr} is the coefficient of rolling resistance; and θ is the segment's incline. Overlines indicate the average value for each segment.

2.8 | Statistics

Normality of the data was assessed using the Shapiro-Wilks test of normality ($\alpha = 0.05$) and visual inspection of Q-Q plots. Data are presented as mean ± standard deviation (SD). For statistical tests, a level of $P \leq .05$ was considered significant, and $P \leq .10$ was considered a tendency. Between-group differences (YOS vs ADS) for mean TT speed, mean TT $\dot{V}O_{2dem,}$ and mean regression coefficients were tested with a two-tailed independent Student's t test. The pacing pattern was considered variable if there were statistically significant changes in relative P_{prop} between segments.

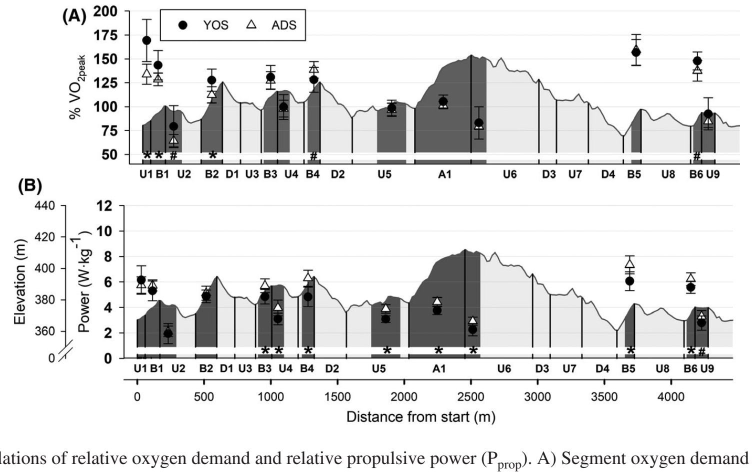


FIGURE 2 Calculations of relative oxygen demand and relative propulsive power (P_{prop}). A) Segment oxygen demand (% $\dot{V}O_{2peak}$), B) P_{prop} (W•kg^{-1}). Data are presented as mean ± SD. *significant between-group differences ($P < .05$). # tendency for between-group differences ($P < .10$). The altitude profile of the racetrack used during the TT is shown behind the data points. The altitude profile for A is the same as B without units. Segments are separated by drop lines. The dark gray area indicates the section of each segment where the athletes skied continuously without using TP and where measurements of $VO2_{dem}$ and P_{prop} were calculated. The calculations for the ADS are averaged for the three laps

Two-factor mixed ANOVAs were conducted to determine whether there were statistically significant between-group differences for speed (2x20 design), and for $\dot{V}O_{2dem}$ and P_{prop} (2x13 design) for the different segments throughout the TT. Mauchly's test was used to test the assumption of sphericity. As the value of epsilon was less than 0.75 when the sphericity assumption was violated, *P* values were adjusted according to Greenhouse-Geisser. Then, a univariate ANOVA was conducted separately on each segment to detect between-group differences. The partial eta squared effect size (η_p^2) was also reported for ANOVA tests, where 0.14 or more, 0.06 or more, and 0.01 or more were considered large, medium, and small effects, respectively.[29]

A two-way ANOVA was conducted on group difference for different gear selections for speed and incline (2 × 5 design). Differences in time using the different gears were analyzed using a one-way ANOVA. Further, one-way repeated measures ANOVA tests were conducted to determine whether there were statistical differences in speed, $\dot{V}O_{2dem}$, and P_{prop} between segments on laps 1-3 for ADS. Bonferroni corrections for multiple comparisons were applied for all ANOVA tests. Pearson's Product Moment Correlation Analysis was applied for correlation of gear choice and TT finishing time. Statistical analyses were performed using SigmaPlot 14.0 (Systat Software, Inc, San Jose, CA) and SPSS statistical package version 24 (SPSS Inc Chicago, IL). In calculations of percent differences between groups, YOS was treated as the reference data (100%).

3 | RESULTS

3.1 | Time trial characteristics

3.1.1 | Speed

Mean TT finishing time was 12:26 ± 1:02 (4.3 km) and 32:06 ± 1:43 min (13.1 km), corresponding to a mean speed of 5.8 ± 0.5 and 6.9 ± 0.3 $m \cdot s^{-1}$, for YOS and ADS, respectively ($F_{1,17} = 16.1$, $P = .001$, $\eta_p^2 = 0.486$). Mean speed for the different segments is shown in Figure 1A. YOS were slower than ADS in all types of terrain inclinations (mean differences of 13 ± 8%), with a hierarchy in differences for uphills (19 ± 10%), undulating terrain (11 ± 5%) and downhills (8 ± 4%) (all, $P < .05$). Time loss ($s \bullet m^{-1}$) for YOS compared to ADS increased when inclination increased (Figure 1B).

The speed profile throughout the TT was different between the groups (interaction effect between group and segment, $F_{3,56} = 4.50$, $P = .005$, $\eta_p^2 = 0.256$). There was no difference in speed between groups for the five first segments. These segments corresponded to 110% and 94% of the mean speed for the whole TT, for YOS and ADS, respectively. YOS skied significantly slower compared to ADS during the remaining segments ($P < .05$) (Figure 1A). For ADS, mean lap speed on the second lap was lower compared to the first and last laps ($F_{2,14} = 4.60$, $P = .03$). There was no difference in segment speed across the three different laps for ADS except for D2 and B5. The speed for D2 on the first lap was higher than on the last lap, and the speed for B5 on the last lap was higher than on the second lap.

3.1.2 | Exercise intensity

The mean relative $\dot{V}O_{2dem}$ calculated from all the segments was 120 ± 14 and 112 ± 10%, of $\dot{V}O_{2peak,}$ YOS and ADS, respectively, with a tendency for higher $\dot{V}O_{2dem}$ for YOS ($F_{1,17} = 3.24$, $P = .089$, $\eta_p^2 = 0.160$). The exercise intensity profile throughout the TT was different between the groups (interaction effect between group and segment, $F_{4,61} = 5.86$, $P = .001$, $\eta_p^2 = 0.256$) and YOS skied at a higher $\dot{V}O_{2dem}$ for the first four segments ($P < .05$ for U1, B1, B2 and $P = .10$ for U2) while there was no difference between groups for the remaining segments (Figure 2A). For ADS, $\dot{V}O_{2dem}$ was higher in U1 on the first lap (start stretch), and in B5 and B6 on last lap (last two uphills) compared to other laps. The remaining segments were similar for the different laps for ADS during the TT.

3.1.3 | Propulsive power

The mean relative P_{prop} calculated from the 13 segments was 4.2 ± 0.6 and 4.8 ± 0.5 $W \bullet kg^{-1}$, YOS and ADS, respectively, and was significantly different between groups ($F_{1,17} = 7.68$, $P = .013$, $\eta_p^2 = 0.311$). The P_{prop} profile throughout the TT was different between the groups (interaction effect between group and segment, $F_{4,60} = 6.76$, $P < .001$, $\eta_p^2 = 0.284$). Both groups displayed variable pacing patterns, shown by the large variation in P_{prop} between segments (Figure 2B). There was no between-group difference in P_{prop} for the first four and the last segments, while YOS worked at a lower P_{prop} for the seven remaining segments (Figure 2B).

3.2 | Gear selection

A difference in speed was observed for the different gears (simple main effects for gear, $F_{4,85} = 514$, $P < .001$, $\eta_p^2 = 0.960$) as the mean speeds for the different gears were significantly different from each other in both groups (all, $P < .001$) (Figure 3). YOS and ADS used the different gears at different speeds (simple main effects for group, $F_{1,85} = 37.1$, $P < .001$, $\eta_p^2 = 0.304$). Further, the speed profile for the gears was different between groups (interaction effect between group and the different gears, $F_{4,32} = 2,73$,

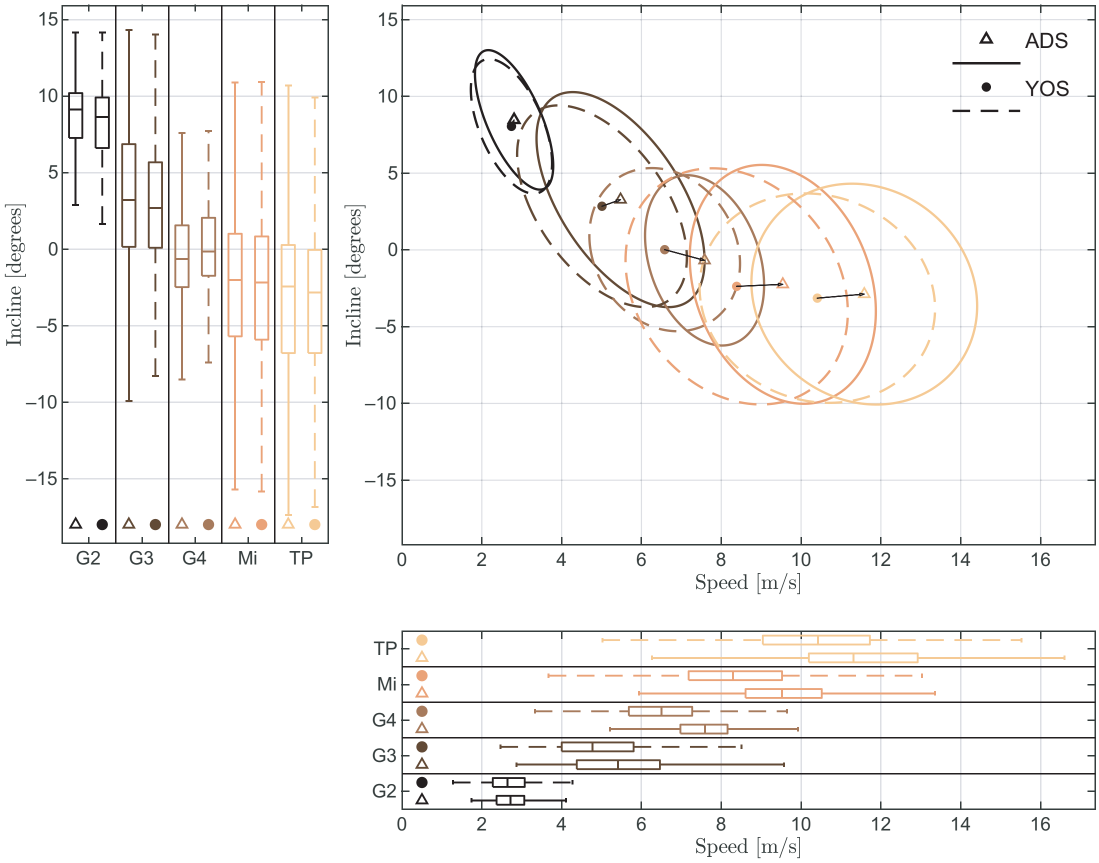


FIGURE 3 Gear selection for the first lap during the TT for YOS and ADS. Dotted ellipses represent YOS, while solid ellipses represent ADS. One ellipse represents 1SD (68%) of the measurement for that particular gear and group. The arrows represent the shift of mean speed and incline for the different gears for YOS compared to the same mean for ADS. On each boxplot, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers. An outlier is a value that is more than 1.5 times the interquartile range away from the top or bottom of the box

P = .035, $\eta_p^2 = 0.114$) as there was a significant difference in speed between groups for G4 ($F_{4,85} = 14.5$, $P < .001$, $\eta_p^2 = 0.145$), Misc., ($F_{4,85} = 14.1$, $P < .001$, $\eta_p^2 = 0.143$) and TP ($F_{4,85} = 16.6$, $P < .001$, $\eta_p^2 = 0.163$) and a tendency for G3 ($F_{4,85} = 2.7$, $P = .10$, $\eta_p^2 = 0.310$).

A difference in incline was observed for the different gears (simple main effects for gear, $F_{4,85} = 857$, $P < .001$, $\eta_p^2 = 0.976$), but YOS and ADS used the different gears at similar inclines (simple main effects for group, $F_{1,85} = 0.48$, $P = .828$, $\eta_p^2 = 0.001$). However, the incline profile for the gears was different between groups (interaction effect between group and the different gears, $F_{4,85} = 2{,}89$, $P = .027$, $\eta_p^2 = 0.119$) as there was a significant difference in incline between groups for G4 ($F_{1,85} = 7.57$, $P = .007$, $\eta_p^2 = 0.082$). YOS used more G2 and less G3 compared to ADS during the TT (Figure 4). Furthermore, individual data from all skiers show that more use of G2 during the TT indicated longer finishing times (r = .88), while more use of G3 during the TT indicated shorter finishing times ($r = -.85$). The number of gear transitions per km was higher for YOS (18 ± 2) than ADS (15 ± 3) (P = .03). YOS changed to TP at a lower speed than ADS (9.2 ± 1.9 $m{\cdot}s^{-1}$ vs 10.2 ± 1.4 $m{\cdot}s^{-1}$, respectively, $P < .05$).

3.3 | Laboratory tests

The relative sub-maximal workload was similar between groups: P_{prop} 2.2-3.1 $W{\bullet}kg^{-1}$; relative VO_{2dem} 64%-84% of $\dot{V}O_{2peak}$ and RPE 11-16. $\dot{V}O_{2peak}$, MAOD (64.9 ± 15.2

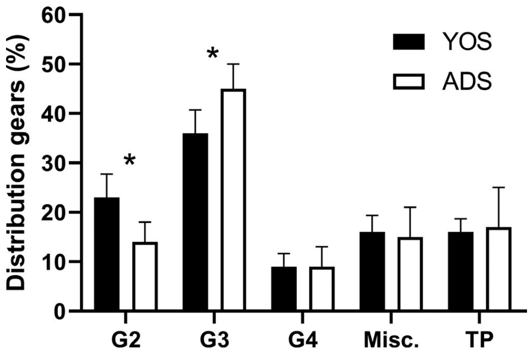


FIGURE 4 Distribution of gears as a percentage of total lap time for the first lap for YOS and ADS. Data are presented as mean ± SD. * significantly different between groups ($P < .01$)

vs 82.6 ± 18.4 mL•kg^{-1}) and mean P_{prop} (4.5 ± 0.5 vs 5.1 ± 0.4 W•kg^{-1}) during the maximal tests were lower for YOS compared to ADS (all $P < .05$).

C was linearly related to F_{prop} for both groups, having a coefficient of determination $R^2 = 0.972 \pm 0.025$ and $R^2 = 0.997 \pm 0.002$ for YOS and ADS, respectively, when the model was applied to each athlete individually. The regression coefficients averaged for the athletes in the two groups were β_1=41 ± 1.0 and 3.3 ± 0.3 μL•J•kg^{-1} and β_2=42.6 ± 20.4 and 30.0 ± 9.02 μL•m•kg^{-1} for YOS and ADS, respectively. β_1, reflecting O_2 cost per external work, was higher for YOS compared to ADS $P = .03$).

4 | DISCUSSION

4.1 | Time trial characteristics

This is the first study to show that young skiers apply the same variable pacing to their adult counterparts when racing an age-related competition distance. YOS showed a highly variable metabolic energy requirement over the course with $\dot{V}O_{2dem}$ exceeding the maximal aerobic power in the uphills and $\dot{V}O_{2dem}$ below maximal aerobic power in flatter terrain, corresponding to findings for adult XC-skiers in previous studies.[1,4,14]

Although XC-skiing is an endurance sport relying greatly on aerobic energy turnover, the anaerobic turnover may be an important contributor to performance for XC-skiers.[27] As skiers repeatedly attain substantial oxygen deficits in individual uphills,[4] anaerobic energy turnover and subsequent recovery from these anaerobic bursts seems as an important piece of the performance puzzle for XC-skiing. The difference between groups for VO_{2peak} and MAOD relative to body mass was ~20%-25% and in line with previous findings.[8,9] Therefore, the similar relative $\dot{V}O_{2dem}$ for uphills between groups indicates that YOS use the same relative fraction of their anaerobic capacity as ADS.

Speed was, however, lower for YOS compared to ADS in all types of terrain, with the largest difference in the uphills, as previously found when comparing male and female elite XC-skiers during a race with similar relative exercise intensity.[14] This is expected, as uphill performance is highly related to maximal aerobic power and is the major determinant of overall performance in XC-skiing.[2,4] However, although the speed difference between groups for uphills (~19%) was larger than for undulating terrain (~11%), the corresponding difference for P_{prop} was similar in both terrains (~16% and ~17%, respectively). Hence, the difference in speed was smaller between groups for undulating terrain than for uphills with similar differences in P_{prop}, as previously found between male and female elite skiers.[14] At high speeds on undulating terrain, a larger part of the P_{prop} is used to overcome air drag compared to uphills because of the quadratic increase in air drag with increasing speed. However, the trade-off between investment of energy reserves and subsequent speed gained in various terrain is not fully understood and is an important aspect for further studies.

YOS demonstrated a higher effort during initial phases of the TT compared to ADS, and thereby a more pronounced positive pacing. For endurance sports with durations exceeding 2-3 minutes, such as distance XC-skiing, an even strategy seems the best choice.[5,30] Evidently, elite male XC-skiers have a more even lap-to-lap pacing compared to their slower counterparts[6,15] and older and more experienced skiers seem to adopt a more even pacing than their younger counterparts of similar performance level.[16,17,31] This imply that young skiers could benefit from adopting a more conservative pacing to enhance their performance. Furthermore, the acquisition of pacing skill seems to develop during adolescence, and as with adult athletes, better-performing adolescent athletes seem to have more optimal pacing than their slower counterparts.[12] As learning to optimize pacing is an important characteristic for the performance of young athletes,[11,12] incorporating training in this skill could be an important part of optimizing performance for young skiers.

It should be acknowledged that YOS only competed for approximately 40% of the time ADS competed in the current study. This was done to keep a high ecological validity as this is close to normal race distance for YOS. Further, most of YOS had never raced more than five km before and pacing may be affected by experience.[12] Since exercise intensity and duration are closely linked, the difference in duration could potentially affect the comparison of exercise intensity between groups in the present study. This could be the reason for the slightly higher relative exercise intensity for YOS compared to ADS (120% vs 112%). However, analyses of FIS world-cup races over the last decades, (Losnegard 2013, p. 3) show that the mean speed for different individual XC-skiing competitions, ranging from 5k to 30k is not significantly different in elite XC-skiers.[30] Therefore, the findings in the present study would probably be comparable even if ADS had competed for a shorter distance.

Since the calculated exercise intensity for the different segments for ADS is the mean over three laps, the pacing could possibly affect the results if the exercise intensity changed throughout the TT. When comparing the segment $\dot{V}O_{2dem}$ between laps for ADS, there was a difference in U1, B5, and B6. The rest of the sections were similar between laps. U1 on the first lap had a higher $\dot{V}O_{2dem}$ than on the 2nd and 3rd lap, indicating the high cost of acceleration at the start from a stand-still position. B5 and B6 on the last lap had a higher $\dot{V}O_{2dem}$ than on the first two laps, indicating an end spurt. However, when comparing these three segments isolated (U1 on first lap, B5 and B6 on last lap) with the same segments for YOS, YOS still had a higher $\dot{V}O_{2dem}$ for U1 and there was still no difference between groups for B5 and B6.

4.2 | Technique characteristics

The significant difference in speed between groups affected gear selection in uphills, where YOS used more G2 and less G3 than ADS (Figure 4). Overall, for both groups merged, the use of G3 was correlated with faster finishing times, as found previously, suggesting that speed is the major factor for gear selections.[2,3,14,15,32,33] Both groups used the different gears within the normal speed ranges as proposed by Losnegard (2019).[34] However, a novel finding is the significant difference in speed between groups for gear selections, where YOS used G4, Misc., and TP at lower speeds than ADS, as well as showing a tendency for lower speed for G3 (Figure 3). This indicates that there could be other indirect factors that influence gear selection other than speed. With increasing speed, the time window for the propulsion phase decreases and limits the possibility to generate force.[19] G3 relies more on propulsion forces from the upper body compared to G2,[35] and the force exerted through the poles relative to body weight may be a potential trigger signal for gear transition.[32] Since the contribution from the upper body is an important performance characteristic for high-speed gears[36] and poling forces are estimated to cost as much as 40 times more than ski force generation,[35] combined with the assumption of better upper body strength and oxidative capacity in ADS than in YOS, this may have affected the different gear speeds observed between groups in the present study.

YOS changed gears more often than ADS, mainly because YOS changed to G2 in several uphills when ADS continued with G3. When investigating individual data, many skiers in YOS changed to G2 in the area of the spikes for instantaneous time loss in Figure 2B. This could be due to loss of speed in the transition between gears as previously suggested.[2] Practicing efficient transitions between gears could therefore be important for performance and a skill that should be acquired during adolescence.

4.3 | Methodological considerations

Methods to determine $\dot{V}O_{2peak}$ and MAOD were different between groups. The adult skiers were participants in a previously published article by Gløersen et al. (2020). The TT_{1000m} test is a regular test protocol for elite male skiers in our laboratory, and the ADS were well accustomed to the test. The initial start speed (corresponding to ~70 mL•kg^{-1}•min^{-1}) was evaluated as being not appropriate for the adolescents. Furthermore, YOS were already part of another project in which they performed the TT_{3min} using G2. We chose to use the results from this test to keep the test load on the young skiers as low as possible. Both maximal tests have been shown to be valid methods for determining $\dot{V}O_{2peak}$ during treadmill roller skiing,[28] and MAOD seems independent of the sub-techniques G2 and G3.[1,28] The small difference in incline (6° vs 8°) between groups may have affected MAOD.[1] However, this possible difference should not have affected the main results of this study, which was the comparison of relative exercise intensity between the two groups. During the two maximal tests (TT_{1000m} and TT_{3min}), the skiers used wheels with a lower C_{rr} (wheel type 1) than during the sub-maximal efforts and the TT (wheel type 2). The reason for this is that wheel type 1 is the standard for the regular test protocol TT_{1000m} and the same wheel type was evaluated as being best suited for the other project YOS participated in, while wheel type 2 has a C_{rr} more similar to regular XC-skiing on snow and was therefore used during the TT and sub-maximal efforts. However, this does not affect the results in the present study. Furthermore, the rolling resistance has been found to be similar between the treadmill and on asphalt.[21] However, the rolling resistance used in the present study may differ from the resistance between the skis and the snow during winter competitions. This may potentially affect the pacing of XC-skiers, but the difference between groups would probably stay similar and not affect the results in the present study.

Breath-by-breath measures for $\dot{V}O_2$ were used for ADS, while averaged measures (mixing chamber) were used for YOS. For the purposes of Gløersen's (2020) study, instantaneous measurement of $\dot{V}O_2$ was a key point. Since instantaneous measurements were not needed for YOS, we chose to measure $\dot{V}O_2$ with a mixing chamber, which has been thoroughly validated.[37] However, as relative $\dot{V}O_{2dem}$ is used in the present study to compare groups, this should not affect the results. A detailed description of the validation of the breath-by-breath measures can be found in Gløersen et al (2020), supplemental content 1.[4] The model predicting VO_{2dem} in the present study assumes a linear relationship between VO_{2dem}, speed, and P_{prop}. As the VO_2 slow component becomes apparent during prolonged exercise at exercise intensities above the critical aerobic rate ("threshold" intensity), the model may underestimate the VO_{2dem}, especially during the latter part of the race. This is further discussed in the supplemental content 2 of Gløersen et al (2020).[4] Further, the model does not take into account potential change in *C* throughout the race. The exercise intensity was only calculated where the skiers generated propulsive force, so we do not have the complete intensity profile throughout the race and the mean $\dot{V}O_{2dem}$ for the race.

5 | CONCLUSION

Due to higher effort during the initial phase of the TT, the mean exercise intensity during the TT tended to be higher for young competitive XC-skiers compared to their adult counterparts when racing an age-related distance. Both groups followed the same variable pacing, but the higher initial effort for the young skiers indicated a more pronounced positive pacing compared to their adult counterparts.

The lower speed for YOS in uphills induced more use of G2 for YOS compared to ADS. Furthermore, there was a difference in speed for "high-speed gears" between groups, indicating that there could be indirect factors other than speed influencing gear selection.

6 | PERSPECTIVES

An even pacing for endurance events with durations exceeding 2-3 minutes seems beneficial.[5] Thus, the higher effort for the young skiers during the initial phases of TT may imply that younger skiers could benefit from adopting more conservative pacing to enhance their performance.

The close link between speed and gear selection indicates that the use of "higher gears" is associated with higher speed and thereby higher metabolic cost. Therefore, we do not recommend that younger skiers adopt a similar "gear selection strategy" as adult elite skiers due to differences in physiological capacity. As YOS spend more time in uphill than ADS, uphill endurance training and an effective uphill technique may be of greater importance for this group compared to older and faster skiers. Hence, an improvement in G2 technique efficiency would benefit young skiers and could therefore be prioritized during training until their physiological capacity to achieve higher speeds has improved. Furthermore, a potential focus for younger skiers to prevent time loss is to practice efficient transitions between gears, especially in the uphills.

FUNDING INFORMAION

This study was internally financed by the Department of Physical Performance at the Norwegian School of Sport Sciences.

ACKNOWLEDGEMENTS

The authors thank Magne Lund Hansen and Laurie Assenbaum for their contribution to the data collection and data analysis.

CONFLICT OF INTEREST

There are no conflicts of interest, including financial, consultant, institutional, or other relationships that might lead to bias or conflict of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

AUTHORS' CONTRIBUTIONS

OS, ØG, and TL designed the study. OS, ØG, MG, and TL performed the data collection. Data analysis was performed by OS, ØG, and MG. OS, ØG, MG, and TL drafted the manuscript. All authors edited and revised the manuscript. All authors approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request from the corresponding author.

ORCID

Ove Sollie https://orcid.org/0000-0003-4427-5164
Øyvind Gløersen https://orcid.org/0000-0002-5424-6183
Matthias Gilgien https://orcid.org/0000-0003-2181-5922
Thomas Losnegard https://orcid.org/0000-0001-8646-7477

REFERENCES

1. Karlsson O, Gilgien M, Gloersen ON, Rud B, Losnegard T. Exercise Intensity During Cross-Country Skiing Described by Oxygen Demands in Flat and Uphill Terrain. *Front Physiol*. 2018;9:846.
2. Andersson E, Supej M, Sandbakk O, Sperlich B, Stoggl T, Holmberg HC. Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur J Appl Physiol*. 2010;110(3):585-595.
3. Marsland F, Mackintosh C, Holmberg HC, et al. Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition. *PLoS One*. 2017;12(8):e0182262.
4. Gloersen O, Gilgien M, Dysthe DK, Malthe-Sorenssen A, Losnegard T. Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med Sci Sports Exerc*. 2020;52(4):983-992.
5. Abbiss CR, Laursen PB. Describing and understanding pacing strategies during athletic competition. *Sports Med*. 2008;38(3):239-252.
6. Losnegard T, Kjeldsen K, Skattebo O. An Analysis of the Pacing Strategies Adopted by Elite Cross-Country Skiers. *J Strength Cond Res*. 2016;30(11):3256-3260.

7. Stoggl T, Pellegrini B, Holmberg HC. Pacing and predictors of performance during cross-country skiing races: A systematic review. *J Sport Health Sci*. 2018;7(4):381-393.
8. Gaul CA, Docherty D, Cicchini R. Differences in anaerobic performance between boys and men. *Int J Sports Med*. 1995;16(7):451-455.
9. Zwiren LD. Anaerobic and aerobic capacities of children. *Pediatr Exerc Sci*. 1989;1(1):31-44.
10. Menting SGP, Hendry DT, Schiphof-Godart L, Elferink-Gemser MT, Hettinga FJ. Optimal Development of Youth Athletes Toward Elite Athletic Performance: How to Coach Their Motivation, Plan Exercise Training, and Pace the Race. *Front Sports Act Living*. 2019;1(14). https://doi.org/10.3389/fspor.2019.00014
11. Elferink-Gemser MT, Hettinga FJ. Pacing and self-regulation: important skills for talent development in endurance sports. *Int J Sport Physiol*. 2017;12(6):831-835.
12. Wiersma R, Stoter IK, Visscher C, Hettinga FJ, Elferink-Gemser MT. Development of 1500-m pacing behavior in junior speed skaters: a longitudinal study. *Int J Sport Physiol*. 2017;12(9):1224-1231.
13. Bolger CM, Kocbach J, Hegge AM, Sandbakk O. Speed and heart-rate profiles in skating and classical cross-country skiing competitions. *Int J Sports Physiol Perform*. 2015;10(7):873-880.
14. Andersson EP, Govus A, Shannon OM, McGawley K. Sex differences in performance and pacing strategies during sprint skiing. *Front Physiol*. 2019;10:295.
15. Welde B, Stoggl TL, Mathisen GE, et al. The pacing strategy and technique of male cross-country skiers with different levels of performance during a 15-km classical race. *PLoS One*. 2017;12(11):e0187111.
16. Carlsson T, Carlsson M, Hammarstrom D, Ronnestad BR, Malm CB, Tonkonogi M. Optimal [Formula: see text] ratio for predicting 15 km performance among elite male cross-country skiers. *Open Access J Sports Med*. 2015;6:353-360.
17. Nikolaidis PT, Villiger E, Knechtle B. Older recreational cross-country skiers adopt more even pacing strategies than their younger counterparts of similar performance level. *Res Sports Med*. 2019;27(3):365-373.
18. Nikolaidis PT, Villiger E, Rosemann T, Knechtle B. The effect of aging on pacing strategies of cross-country skiers and the role of performance level. *Eur Rev Aging Phys Act*. 2018;15:4.
19. Nilsson J, Tveit P, Eikrehagen O. Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomech*. 2004;3(1):85-107.
20. Solli GS, Kocbach J, Seeberg TM, et al. Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *PLoS One*. 2018;13(11):e0207195.
21. Gloersen O, Losnegard T, Malthe-Sorenssen A, Dysthe DK, Gilgien M. Propulsive power in cross-country skiing: application and limitations of a novel wearable sensor-based method during roller skiing. *Front Physiol*. 2018;9:1631.
22. Hoffman MD, Clifford PS, Bota B, Mandli M, Jones GM. Influence of body-mass on energy-cost of roller skiing. *Int J Sport Biomech*. 1990;6(4):374-385.
23. Losnegard T, Mikkelsen K, Ronnestad BR, Hallen J, Rud B, Raastad T. The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. *Scand J Med Sci Sports*. 2011;21(3):389-401.
24. Borg G. Physical performance and perceived exertion. *Dissertation*. Lund; 1962.
25. FIS. FIS Cross-Country Homologation Manual. In: FIS, ed2019.
26. Gilgien M, Sporri J, Limpach P, Geiger A, Muller E. The Effect of Different Global Navigation Satellite System Methods on Positioning Accuracy in Elite Alpine Skiing. *Sensors-Basel*. 2014;14(10):18433-18453.
27. Losnegard T, Myklebust H, Spencer M, Hallen J. Seasonal variations in VO2max, O2-cost, O2-deficit, and performance in elite cross-country skiers. *J Strength Cond Res*. 2013;27(7):1780-1790.
28. Losnegard T, Myklebust H, Hallen J. Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc*. 2012;44(4):673-681.
29. Cohen J. Statistical power analysis for the social sciences; 1988.
30. Losnegard T.Physiological determinants of performance in modern elite cross-country skiing. Dissertation. Norwegian School of Sport Sciences; 2013.
31. Nikolaidis PT, Rosemann T, Knechtle B. The differences in pacing among age groups of amateur cross-country skiers depend on performance. *J Hum Kinet*. 2019;66:165.
32. Pellegrini B, Zoppirolli C, Bortolan L, Holmberg HC, Zamparo P, Schena F. Biomechanical and energetic determinants of technique selection in classical cross-country skiing. *Hum Mov Sci*. 2013;32(6):1415-1429.
33. Losnegard T, Myklebust H, Hallen J. No differences in O2-cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines. *J Strength Cond Res*. 2012;26(5):1340-1347.
34. Losnegard T. Energy system contribution during competitive cross-country skiing. *Eur J Appl Physiol*. 2019;119(8):1675-1690.
35. Smith G, Kvamme B, Jakobsen V.Effectiveness of ski and pole forces in ski skating. Science and Skiing IV ed: Maidenhead (UK): Meyer & Meyer Sport; 2009.
36. Sandbakk O, Ettema G, Holmberg HC. Gender differences in endurance performance by elite cross-country skiers are influenced by the contribution from poling. *Scand J Med Sci Sports*. 2014;24(1):28-33.
37. Foss O, Hallen J. Validity and stability of a computerized metabolic system with mixing chamber. *Int J Sports Med*. 2005;26(7):569-575.

How to cite this article: Sollie O, Gløersen Ø, Gilgien M, Losnegard T. Differences in pacing pattern and sub-technique selection between young and adult competitive cross-country skiers. *Scand J Med Sci Sport*. 2020;00:1–11. https://doi.org/10.1111/sms.13887

Paper IV

Received: 21 May 2021 | Accepted: 29 July 2021
DOI: 10.1111/sms.14030

ORIGINAL ARTICLE

WILEY

Observational vs coaching feedback on non-dominant whole-body motor skill performance — application to technique training

Ove Sollie[1] | Kristian Holmsen[1] | Christian Steinbo[2] | Yngvar Ommundsen[2] | Thomas Losnegard[1]

[1]Department of Physical Performance, Norwegian School of Sports Sciences, Oslo, Norway
[2]Department of Sport and Social Sciences, Norwegian School of Sports Sciences, Oslo, Norway

Correspondence
Ove Sollie, Department of Physical Performance, Norwegian School of Sport Sciences, Sognsveien 220, PO Box 4014 Ullevål Stadion, 0806 Oslo, Norway.
Email: ove.sollie@nih.no

Funding information
This study was internally financed by the Department of Physical Performance at the Norwegian School of Sport Sciences

We studied the effect of peer- and self-observational feedback versus coaching feedback during technique training on performance in competitive adolescent cross-country skiers. Fifty-four skiers (14.3 ± 0.6 years) were divided into a control group and three intervention groups (dyad practice, video, or coaching feedback), which practiced in the asymmetrical uphill sub-technique G2 on one side (non-dominant side), but not the other (dominant side) for 6 × 30 min over a 5 weeks period, on roller skis outdoors. High-speed performance and skiing economy were assessed on a roller ski treadmill before and after the intervention, and a questionnaire was answered post-intervention. The video feedback ($p = .025$, $d = .65$) and coaching feedback ($p = .007$, $d = .89$) groups improved high-speed performance during the intervention and an ANCOVA showed a tendency for different change scores between interventions ($F_{3,49} = 2.5$, $p = .068$, $\eta_p^2 = .134$), with a difference between the coaching feedback and dyad practice ($p = .05$). No change was seen in skiing economy in any group. Coaching feedback ranked higher on enjoyment compared with dyad practice ($p < .001$) and led to higher self-perception of improved technique compared with the control group ($p = .038$). Overall, feedback from a competent coach seems better than observation for improving performance in young athletes, although self-observation through video with attentional cues seems a promising tool for increasing individual feedback when coaching large groups.

KEYWORDS
dyad practice, motor learning, motor performance, practice efficiency, talent development, video feedback

1 | INTRODUCTION

Athletic development is multifaceted and is based on a complementary mix of athletic attributes and skills to be acquired and improved.[1] One of the pillars of endurance performance is the ability to transform metabolic energy efficiently into speed.[2,3] This is coupled with an "efficient technique," which can be defined as "the relative position and orientation of body segments as they change during the performance of a sport task to perform that task effectively".[4] Although key identifiers of such efficient sport-specific techniques have been widely studied,[4] less is known about how these are acquired in an applied practice setting.

Technique training in applied settings aims to implement deliberate practice, which facilitates beneficial technique modifications and results in a more efficient technique and improved performance. In applied youth sport practice settings, this most often occurs in groups with a high athlete-to-coach ratio, which restricts coaches' opportunities to provide individual feedback.[5] Thus, organizing practice sessions to facilitate more individual feedback is an important aspect of technique training. However, previous research has been based on interaction with a single participant at a time[5] and few ecologically valid feedback studies from applied sport practice settings exist.[6]

Augmented feedback is one of the most important features for acquiring and improving sport-specific technique.[7] In applied sport practice settings, the coach often provides augmented feedback to facilitate the process of acquiring a more efficient technique. However, a coach does not necessarily provide feedback that facilitates this process optimally.[8] Furthermore, in youth sports, the coach is often a non-professional, such as a parent or other volunteer with limited content knowledge both of efficient sport-specific technique and of how to effectively promote this technique.

Observation of others, or oneself, is frequently used to assist athletes' learning processes in applied sport practice settings[9] and may enhance learning[6,10] as well as increasing learners' motivation.[11] Two observational methods promoting more individual feedback are peer-model observation through dyad practice, where two athletes interactively observe and instruct each other, and conducting self-observation through video.[6,11] Dyad practice may increase cognitive involvement,[11] as well as ownership of and responsibility for the learning process, and consequently improve motor learning.[12] Today's smartphones, with large high-resolution screens, may provide practice settings where multiple individuals receive immediate viewable feedback simultaneously[5] with positive performance outcomes.[13] However, the results from using video feedback for performance outcomes have been equivocal,[6] implying the need to reduce the information given to young athletes. Therefore, video feedback with attentional cues, where the athlete's attention is directed to the most appropriate aspects of the technique, can accelerate the process of beneficial technique modification[14,15] and has been shown to be superior to video feedback only.[16] Both verbal and visual cuing have been shown to facilitate the acquisition of efficient technique.[17] However, in applied sport practice settings with a high athlete-to-coach ratio, feedback methods with cueing promoting more individual feedback should be explored. As such, written cue cards may give attentional cues to multiple athletes simultaneously in applied sport settings.

The movement pattern in cross-country (XC) skiing consists of a complex interaction between upper and lower body where movement patterns are categorized into different sub-techniques. In the asymmetrical uphill sub-technique G2, skiers have a dominant and a non-dominant side. This technique is therefore well suited to assess the effect of different feedback methods and assessing improvement in technical execution for complex movement patterns since within-individual comparisons can be made, as skiers can practice the non-dominant side while the dominant side acts as a control for physiological responses. In this way, we can distinguish between technical and physiological changes during an intervention. In sports, deliberate technique practice needs to facilitate increased performance (or fewer injuries) to have relevance for the athlete. We therefore compared two observational feedback methods with feedback from a competent coach on performance changes on the non-dominant side in the XC-skiing G2 skating technique, where all groups used cue cards to control the content of feedback information.

2 | MATERIAL AND METHODS

2.1 | Participants

Fifty-four adolescent competitive XC-skiers participated in the study (Table 1). The athletes were recruited from four local XC-ski clubs. Inclusion criteria were (1) attending local club training regularly; (2) participating in regional and/or national XC-skiing competitions; (3) experience with roller skiing; and (4) for intervention groups, attending minimum five of six practice sessions (6/6: 24 participants, 5/6: 17 participants). Participants and their parents were informed of the nature of the study and the possible risks involved before giving their written consent. The study was approved by the Human Research Ethics Committee of The Norwegian School of Sport Sciences and registered with the Norwegian Centre for Research Data.

TABLE 1 Characteristics of the skiers at pre-intervention test

	Boys (n = 27)	**Girls (n = 27)**
Age (years)	14.2 ± 0.6	14.3 ± 0.6
Body mass (kg)	57.2 ± 7.7	55.9 ± 8.1
Body height (cm)	172.1 ± 7.4	166.8 ± 4.9
Roller ski G2 VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)*	61.9 ± 5.6	53.5 ± 5.8
Weekly training (h)*	9.3 ± 3.6	8.6 ± 3.2

Note: Data are reported as mean ± standard deviation.

*Weekly training was self-reported, VO_{2peak} was measured on the dominant side in the G2 skating technique.

2.2 | The G2 skating sub-technique

Competitive XC-skiing consists of two main techniques (classic and skating) each with several sub-techniques. The choice of sub-technique depends mainly on speed and therefore acts as a "gearing system".[18] The uphill skating sub-technique Gear 2 (G2, also called V1 or "paddling") is characterized by asymmetrical double poling action during leg push-off on the "strong side," but not on the "weak side" (Figure 1). Most skiers have a preferred "strong side" either to the left or right side of the body (dominant side) and changing the "strong side" to the other side of the body (non-dominant side) is used less and usually with less efficient technique.[19,20] In the present study, all participants had a clear-cut opinion of which side was dominant and which was non-dominant (30 and 24 athletes with the dominant side to the right and left, respectively).

2.3 | Apparatus

A detailed description of the apparatus used in the present study can be found in Losnegard et al. (2012).[21] Testing procedures and apparatus used were identical pre- and post-intervention tests. All testing was performed on a roller ski treadmill and identical roller skis, and poles were used pre- and post-intervention. The athletes used their own equipment during the intervention training sessions. No technique instruction was given during laboratory testing. All tests were performed using the G2 technique.

2.4 | Experimental overview

The athletes performed two familiarization sessions before the main test session pre-intervention (Figure 2, upper panel). During the 5 weeks intervention period, the athletes performed 6x ~ 30 min practice sessions on roller skis using the G2 technique on the non-dominant side, before a new main test session post-intervention. The performance testing pre- and post-intervention was performed on a roller ski treadmill and performance outcomes were the change scores from the pre- to post-intervention in maximal relative power output from an incremental speed test and skiing economy during submaximal roller skiing. The athletes were divided into a control group and three intervention groups. The feedback methods during the intervention were Dyad practice (DYAD), Video feedback (VIDEO), and Feedback from an expert coach (COACH). The control group (CON) performed only the test sessions pre- and post-intervention, with no intervention practice sessions in between. The intervention groups used identical attentional cue cards to control the content of feedback information. The timing, frequency, and amount of feedback were identical between groups (Table 2).

2.5 | Testing

Familiarization: The skiers completed two familiarization sessions in which they became thoroughly accustomed to the treadmill and the different tests using the same apparatus that would be used during the main test sessions. All participants followed the same familiarization protocol. The first familiarization consisted of 30 min of submaximal roller ski skating before completing two incremental speed tests (see later). The second familiarization session consisted of a 10 min easy self-paced warm-up and two 5 min submaximal G2 efforts with cardiorespiratory measurements for familiarization with the equipment.

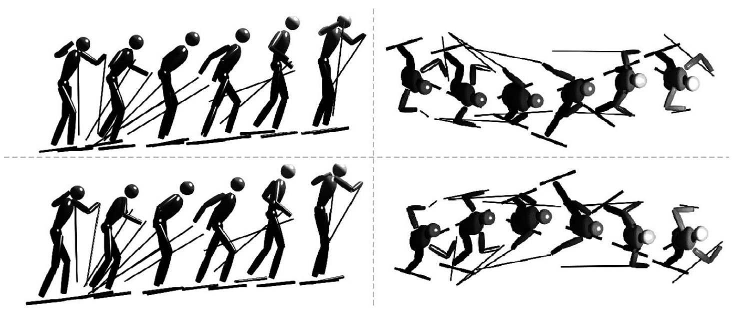


FIGURE 1 One cycle for G2 skating technique starting with pole plant on the strong side. Upper panel shows a side view (left) and top view (right) of the strong side to the right. Bottom panel shows a side view (left) and top view (right) of the strong side to the left. For most skiers, one side is the dominant side, with the other being the non-dominant side

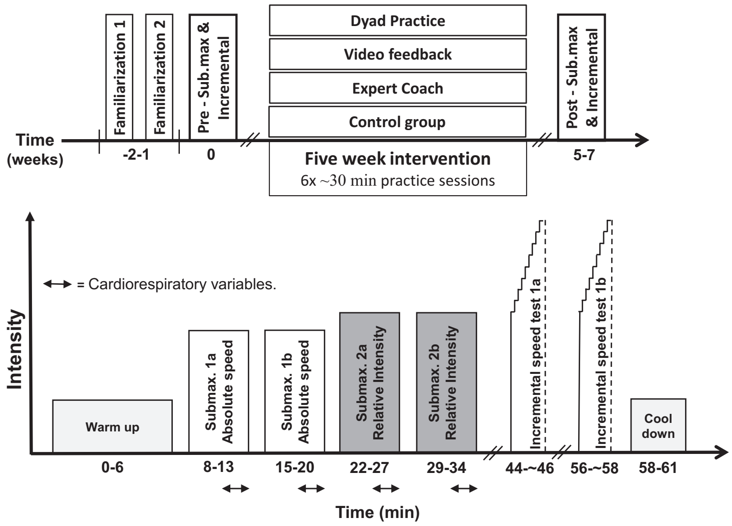


FIGURE 2 Upper panel: Overview of the experimental design. Bottom panel: Overview of the treadmill test session pre- and post-intervention. Submax. workloads 1a and 1b were performed at the same speed for all participants. Whether 1a or 1b was on the dominant side was randomized for each participant. Submax. workloads 2a and 2b were performed at ~83% of $\dot{V}O_{2peak}$ in the same order as 1a and 1b. All submaximal workloads were performed at 6°C incline. Incremental speed tests 1a and 1b were performed in the same order as the submaximal workloads at 8°C incline. The order of dominant vs. non-dominant side followed the same order during the post-intervention tests

TABLE 2 An overview of the attentional cues/questions from each session

Session focus	Session number	Attentional cues/ questions	
Rhythm	1 and 4	Main question	What do you think about the rhythm?
		Secondary questions	Do two poles and one ski hit the ground at the same time?
			Are the movements "smooth and flowing" or are they "jagged"?
Sideways weight transfer	2 and 5	Main question	What do you think about the weight transfer from ski to ski?
		Secondary questions	Does the upper body follow the same direction as the skis?
			Do you push with both poles and skis actively?
Overall technique	3 and 6	Questions	What is good about your technique?
			What can be improved about your technique?

Note: The questions are translated from Norwegian

Time-trial: At the end of the second familiarization day, a 3 min time-trial ($TT_{3\ min}$) was performed to assess cardiorespiratory variables and performance ($\dot{V}O_{2\ peak}$ and distance). $TT_{3\ min}$ started on an 8 incline and 2.25 $m{\cdot}s^{-1}$ for the boys and 2.0 $m{\cdot}s^{-1}$ for the girls. This speed was fixed during the first 30 s to prevent the participants from starting too fast. Thereafter, the test was performed paralleling procedures as the sprint test reported in Losnegard et al. (2012).[21] The test was performed twice, once on the dominant side and once on the non-dominant side, in a randomized order, separated by a 10 min break.

2.5.1 | Main test session

An overview of the testing session is illustrated in Figure 2, bottom panel. Before the pre-intervention test session, the order of dominant vs. non-dominant side was randomized and the participants used the two different sides every other time for the different work bouts throughout the test session. The participants followed the same order during the post-intervention test session.

Submaximal workloads: An easy self-paced 6 min warm-up, 3 min on the dominant and 3 min on the non-dominant side, was completed using the G2 technique before four 5 min submaximal work bouts. The results from the first two 5 min steady-state stages are not discussed in this paper. Thereafter, the subjects completed two further 5 min efforts at a pace corresponding to the same estimated relative intensity (~83% of $\dot{V}O_{2\ peak}$, 6°C incline). Cardiorespiratory variables and heart rate were monitored from 2 to 5 min, and the averages for 2.5–5 min provided the steady-state values used for further analysis. Each 5 min bout was separated by a 2 min break.

Incremental speed test: The speed test was performed 10 min after the last submaximal work bout on both dominant and non-dominant sides, separated by a 10 min break. The incline was set to 8°C, with a starting speed of 2.5 m/s (estimated O2-cost of ~66 $ml \cdot kg^{-1} \cdot min^{-1}$). The speed then increased automatically by 0.25 m/s every 15 s (estimated increase of ~7 $ml \cdot kg^{-1} \cdot min^{-1}$). Thereafter, the athletes adjusted their position on the treadmill as in $TT_{3\ min}$. The test was terminated manually by the test leader when the skiers could not keep the front wheels of their roller skis in front of a laser beam projected on to the treadmill behind the skiers for two consecutive cycles. HR was measured throughout the test. P_{max} from the speed test was determined as:

P_{max} = Workload for the last step completed + [(Increase in workload for each step/duration of each step) x duration of final step].

2.6 | Feedback intervention

All groups performed the intervention at the same time of the season (September-October). The four XC-skiing clubs were randomly assigned to an intervention group or to the control group, and no club had skiers in more than one group. The number of boys and girls in each group was given by the skiers volunteering for the study from each XC-skiing club.

2.6.1 | Practice sessions

Each intervention practice session lasted ~30 min and was designed so the groups had the same timing, frequency and amount of practice time (3 × 5 min) and feedback time (2 × 5 min) during each session. The practice was only performed on the participants' non-dominant side. All groups used the same written cue cards to control the feedback information given and to guide the attention of the athletes to the session focus and corresponding appropriate movements (Table 2). The athletes were observed/filmed from the front in all intervention groups. In four of the training sessions, the athletes worked on specific tasks/questions, while in two of the training sessions (sessions 3 and 6), the questions were more open (Table 2). The list was designed combining findings from previous research on the G2 technique [22] with the experience of professional XC-skiing coaches. All groups practiced at low intensity, competition speed, and sprints for each of the three types of sessions.

2.6.2 | Groups

Dyad practice (DYAD): The skiers (10 boys, 3 girls) formed pairs and observed each other and gave feedback on two runs for each of the two feedback periods. In training sessions with uneven number of skiers, one group of three skiers worked together with two observers to each practicing skiers. The observer gave feedback to the practicing athlete immediately after each run based on the cue cards. The skiers receiving the feedback were encouraged to ask questions and discuss the feedback. The partners were the same throughout each session but changed between sessions.

Video feedback (VIDEO): The skiers (5 boys, 10 girls) formed pairs and filmed each other with their own smartphones for two runs each of the two feedback periods. In training sessions with uneven number of skiers, a group of three skiers worked together. The rest of the feedback period was used to evaluate the videos of themselves using the cue cards before they practiced based on the cues they got from studying the video. No other instruction was given to the participants.

Coaching feedback (COACH): The skiers (7 boys, 6 girls) were separated into three smaller groups, each trained by an experienced XC-skiing coach (all with 10+ years of experience). The three coaches were the same throughout the intervention. The coaches used the same attentional cue cards for feedback as the other groups. Further, the coaches gave coaching cues that were evidence-based, with an external focus of attention and an autonomy-supportive instructional language to facilitate learning.[23,24] The athletes followed a rotational system such that none of the groups were the same for more than one training session and the athletes were coached by the same coach twice during the intervention. Further, before each practice session the coaches agreed on the feedback information given for each of the attentional cues and for the different variations of technical execution that could occur. The participants received feedback after two runs in each of the two feedback periods. The participants knew the focus of the session cue cards, and they were always asked their own opinion regarding their technical execution in relation to the attentional cues/questions before receiving feedback from the coach.

Control group (CON): The skiers (5 boys, 8 girls) did not attend any intervention practice session but continued with their normal training regime. They were not instructed or given any information with respect to whether they should practice the non-dominant side or not. They followed the same test procedures with the same time period between tests as the intervention groups.

2.7 | Questionnaire

After the post-intervention tests, the intervention groups self-reported on three items, while the control group answered only the last two of these items. Items one and two were reported on a 5-point Likert scale. The third question was a self-report on how many times they had practiced on their non-dominant side on their own during the intervention period (Table 3).

2.8 | Statistics

Raw data are presented as mean ± standard deviation (SD) unless otherwise stated. Normality of the data was assessed using the Shapiro-Wilks test of normality ($\alpha = 0.05$). Outliers were assessed by inspection of boxplots and by examination of studentized residuals for values greater than ± 3 (one athlete was removed from the speed test on the dominant side in VIDEO with a value of −3.27). For statistical tests, the level of confidence was set to 95% and a level of $p \leq 0.05$ was considered significant, while $p \leq 0.1$ was considered as a tendency. Relative differences between pre- and post-intervention tests and relative differences between the non-dominant and dominant side are presented as mean ± 95% confidence interval (CI). Changes in P_{max} and $\dot{V}O_2$ from the submaximal workload from pre- to post-intervention were determined using a two-tailed paired Student's *t* test. To detect differences between groups during the intervention, one-way ANCOVA was run on the change scores (Post-Pre) on relative P_{max} from the speed test and $\dot{V}O_2$ and heart rate during the submaximal workloads, to control for pre-intervention scores. The typical error (expressed as CV%) for the speed test was 2.7% (calculated from the familiarization test and the pre-intervention test). We were not able to calculate the typical error for $\dot{V}O_2$ during the submaximal workload for these athletes, but the typical error for elite athletes is 1.2%.[25] Partial eta squared effect sizes (η_p^2) were reported for ANCOVA tests where 0.14 or more, 0.06 or more and 0.01 or more were considered large, medium, and small effects, respectively.[26] Bonferroni corrections for multiple comparison were applied for all ANCOVA and ANOVA tests. The magnitudes of differences between groups and the relative difference between dominant and non-dominant sides were expressed as standardized mean differences (Cohen's *d* effect size-$d < 0.2$ considered to be a very small, 0.2–0.5 a small, 0.5–0.8 a medium and $d > 0.8$ a large effect).[26] A Kruskal-Wallis H test was run to determine whether differences were present between groups for items one and two in the questionnaire. Distributions of each item were assessed by visual inspection of a boxplot. Distributions for the items were not similar between groups. Therefore, we compared mean ranks. Pairwise comparisons were performed using Dunn's (1964) procedures with a Bonferroni correction for multiple comparisons.[27] Adjusted *p*-values are presented and values in parentheses are mean ranks. A one-way ANOVA was performed on item 3.

3 | RESULTS

3.1 | Pre-intervention difference

Differences between dominant and non-dominant sides for the athletes' pre-intervention test scores are shown in Table 4.

3.2 | Speed test (P_{max})

Within-group effects: There was an improvement in high-speed performance (increased time to task failure) (mean ± 95% CI) between pre- and post-intervention tests on the non-dominant side for VIDEO (2.1 ± 1.8%) and COACH (3.8 ± 2.4%) and a tendency for CON (1.7 ± 1.9%),

TABLE 3 Questionnaire the athletes answered after post-testing

Item 1	How much did you like the intervention feedback method?				
	Very unsatisfied	Unsatisfied	Neutral	Satisfied	Very satisfied
Item 2	Have you improved your technique on your non-dominant side?				
	Very unlikely	Unlikely	Neutral	Likely	Very Likely
Item 3	How many times have you trained on the non-dominant side on your own during the intervention?				

Note: The questions are translated from Norwegian.

TABLE 4 Pre-intervention difference between the dominant and non-dominant side for different performance scores. Data are mean and 95% CI

	% dif. between sides ± 95% CI	p	Cohens d
Submaximal skiing economy	1.4 ± 0.8	.001	.10, very small effect
VO_{2peak}	1.7 ± 1.3	.01	.16, very small effect
TT_{3min} performance	5.8 ± 1.6	<.001	.49, small effect
Incremental speed test	6.2 ± 0.9	<.001	.86, large effect

TABLE 5 Relative differences for the speed test from pre- to post-intervention testing

	Dominant side		Non-dominant side	
	p	Cohens d	p	Cohens d
Dyad	.365	.26, small effect	.744	.09, very small effect
Video	.972	.01, very small effect	.025	.65, medium effect
Coach	.312	.29, small effect	.007	.89, large effect
Control	.790	.08, very small effect	.077	.54, medium effect

with no effect for DYAD (−0.2 ± 1.6%). There was no change in performance for the dominant side in any group (Table 5).

Between-groups effect: There was a tendency to a difference in change scores for the non-dominant side between interventions ($F_{3,49} = 2.5$, $p = .068$, $\eta_p^2 = .134$), with a significant difference between COACH and DYAD ($p = 0.05$, diff. of 4.0%, CI 1.2 to 6.7%, $d = 1.18$, large effect) (Figure 3, upper right panel). No difference was found between any of the groups for the dominant side ($F_{3,49} = 0.6$, $p = .608$, $\eta_p^2 = .036$).

3.3 | Submaximal Workloads

Within-group effects: There was no difference between pre- and post-intervention tests for skiing economy ($\dot{V}O_2$) or HR ($p = .11$–$.97$ and Cohens $d = .48$–$.01$) on the non-dominant or the dominant side.

Between-groups effect: No difference in change scores between groups was found for skiing economy ($\dot{V}O_2$) ($F_{3,49} = .67$, $p = .58$, $\eta_p^2 = .039$) (Figure 3, bottom panels) or HR ($F_{3,49} = .76$, $p = .52$, $\eta_p^2 = .045$) on the non-dominant side or the dominant side.

3.4 | Practice

After the post-intervention tests, the athletes answered a questionnaire that used three items (Table 3).

Item 1 (Enjoyment): The mean ranks of scores were different between the three intervention groups, $\chi^2(2) = 16.859$, $p < .001$) showing that COACH (29.96) scored better compared with DYAD (12.35) ($p < .001$) and there was a tendency toward better scores for COACH compared with VIDEO (20.73) ($p = .078$).

Item 2 (Self-perception of improved technique): The mean ranks of scores were different between the groups ($\chi^2(3) = 8.857$, $p = .031$) showing that COACH (32.73) scored better compared with CON (17.58) ($p = .038$).

Item 3 (Number of self-practice): A difference between groups was found for number of self-practices during the intervention for the G2 non-dominant side technique ($F_{3.53} = 8.2$, $p < .001$) where COACH practiced more compared with CON ($p < .001$, mean diff. of 5.4%, CI 2.4%–8.5%) and VIDEO ($p = .03$, mean diff. of 3.1%, CI 0.2%–6.0%) and there was a tendency that DYAD practiced more compared with CON ($p = .054$, mean diff. of 3.0%, CI 0.0%–6.0%). The number of self-practices did not correlate with changes in performance ($r < 0.1$).

4 | DISCUSSION

The aim of the present study was to investigate the effect of observational feedback, providing more individual feedback in groups with a high athlete-to-coach ratio, compared with coaching feedback on performance. We used a novel approach with a long-duration intervention in an applied setting, providing the possibility to investigate intra-individual changes in performance between dominant and non-dominant sides. Our main finding was that high-speed performance improved in COACH and VIDEO from pre- to post-intervention, and that performance improved more in COACH compared with DYAD. Moreover, COACH ranked higher on enjoyment

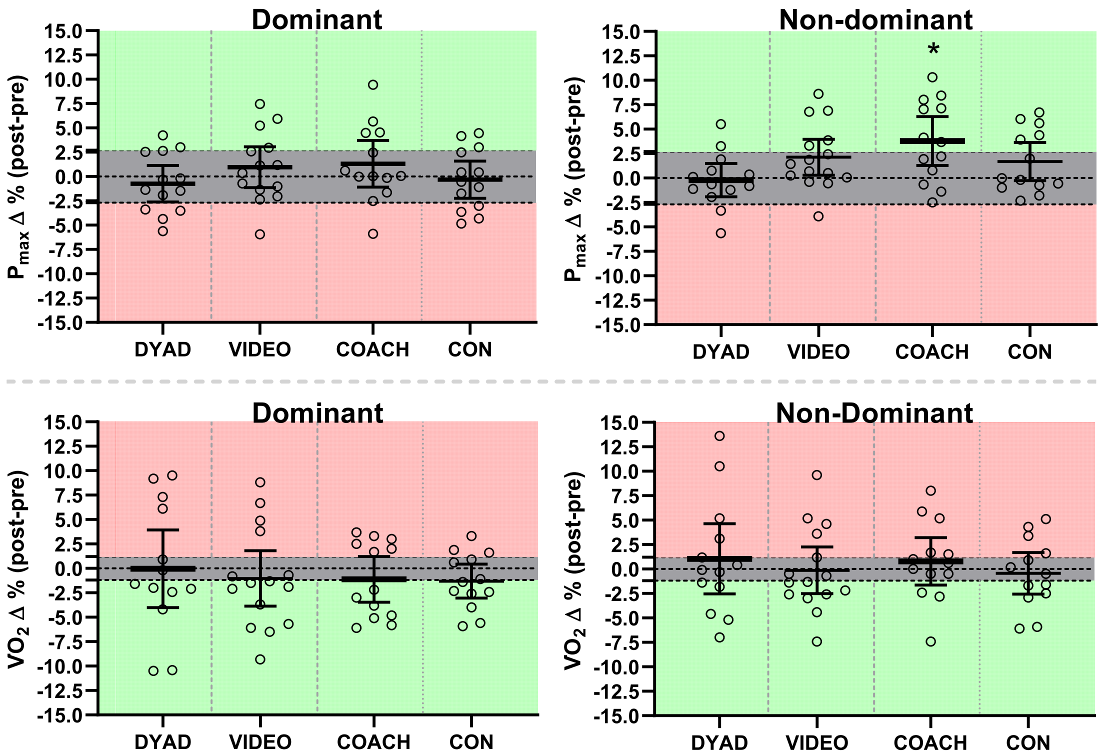


FIGURE 3 Upper panel: Percentage change score from pre- to post-intervention for the speed test. Gray area indicates the typical error of the test expressed as CV of 2.7%. Lower panel: Percentage change score from pre- to post-intervention for $\dot{V}O_2$ on dominant and non-dominant side during submaximal skiing. Gray area indicates the typical error of the test expressed as CV of 1.2% for adult athletes. Mean ± 95% CI. * significantly different from non-dominant side in DYAD controlled for pre-intervention scores. Circles represent individual percentage change scores. The green area indicates enhanced performance during intervention while the red area indicates decreased performance

compared with DYAD and led to higher self-perception of improved technique compared with CON.

To prevent the amount of feedback being different between groups and potentially affecting the results, COACH had three coaches for each session to maintain similar timing, frequency, and cueing between groups. COACH was the only group to reach a large effect size (d = .89) for high-speed performance from pre- to post-intervention and the athletes ranked COACH high on enjoyment. This may imply that coaches can satisfy fundamental psychological needs found to be important, such as enhanced expectancies and positive affect, which may influence learning and performance outcomes in athletes.[24] In addition, COACH showed more self-practice during the intervention compared with CON and VIDEO. More self-practice on the non-dominant G2 technique did not correlate with performance improvement during the intervention, so the improvement in COACH was due to the feedback method and not the amount of self-practice. However, more self-practice over a longer training period might reflect intrinsically regulated motivation for practice,[24] which has been found to positively influence performance in the long run.[28] Therefore, having a low athlete-to-coach ratio in applied group practice settings seems like a good approach for technique training if practically possible. However, applied youth sport practice settings usually do not have this luxury, and furthermore, the coaches may be non-professionals. Therefore, organizing practice sessions where more athletes receive feedback that facilitates beneficial technique modifications can be considered a critical element in the development of efficient technique for youth athletes.

Using the athletes' own smart phones and interactive dyad practice can increase individual feedback in groups with a high athlete-to-coach ratio, but feedback methods need to facilitate beneficial technique modification to have relevance for the athlete. Of the two observational feedback methods, only VIDEO improved high-speed performance during the intervention ($p = .025$, $d = .65$) and the change score adjusted for pre-intervention scores was not different from COACH. VIDEO received no coaching feedback, and obviously, more individual feedback was received per coach compared with COACH, with similar changes in performance. The effect of video feedback on technique improvements has been equivocal,[6] but, in the present study, the attentional cue cards may have helped the athletes to direct their attention to relevant aspects of the technique.[15] Although the change scores between VIDEO and DYAD were not different, only VIDEO improved the high-speed performance from pre- to post-intervention. Athletes' self-observation may be a more powerful tool than observation of others because the self-generated video action is more informative to the athlete due to heightened similarity.[29] Video feedback using athletes' own smart phones with attentional cue cards may therefore serve as a complementary tool for coaches providing technique feedback in large groups.

We included a control group to investigate whether the intervention groups improved more than skiers who did not undertake deliberate practice on the non-dominant side. Although only VIDEO and COACH increased high-speed performance from pre- to post-intervention, CON showed a tendency for increased high-speed performance ($p = .077$, $d = .54$) and there was no difference between COACH, VIDEO, and CON for pre-intervention adjusted change scores. However, CON ranked low on self-perceived technique improvement and this group did not practice the non-dominant G2 technique during the intervention period. Further, control groups in motor learning studies might not be completely "neutral".[24] In this regard, some skiers in CON reported that they were very motivated to perform better on the post-test, even though they did not know the results from the first test. The fact that they were part of an experimental study might therefore have affected the results. Furthermore, there were large inter-individual differences in the physiological responses in the different groups (Figure 3). This may suggest that individual preferences for feedback exist and should be taken into consideration when coaching groups of athletes. Thus, as a coach, one might potentially degrade the level of technique in some athletes if one is not paying attention to individual needs.

A somewhat surprising finding was that DYAD did not improve performance. Although dialogues in the present study were not recorded or formally analyzed, informal observations from DYAD indicated that the athletes often focused on non-relevant movements and gave feedback with an internal focus of attention. It has been repeatedly shown that an external focus of attention facilitates learning[23] and the athletes may have adopted a higher self-focus and thus became overly aware of their movements, which may have reduced motor learning.[24] Participants in collaborative or cooperative learning situations often anecdotally report more enjoyment than they have experienced when learning alone.[30] However, this was not expressed in the present study, where DYAD ranked low on enjoyment. Many of the athletes commented that they thought it was difficult to coach other athletes even though they had the attentional cue cards. VIDEO did not express this view when "coaching" themselves. The athletes' preexisting knowledge of the movement was perhaps too limited to understand how to best instruct another athlete[28] and dyad practice in this case may have been a method better suited for more experienced athletes with higher sport-specific technique content knowledge. Nevertheless, dyad practice has previously been shown to increase participants' feeling of responsibility for and involvement in the learning process, meaning that they were prepared to invest more cognitive effort and to engage in processing activities that they would not have engaged in otherwise.[11] Furthermore, previous research suggests that dyad practice may result in more flexible or generalizable capability,[23] which may facilitate the development of technique in sports consisting of complex movements like XC-skiing. However, in our case the intervention period may have been too short and the preexisting sport-specific technique knowledge of the athletes too limited to be able to verify the potential benefits of such dyadic practice.

As expected, skiing economy on the non-dominant side was less efficient than the dominant side during the pre-intervention test ($n = 54$, Table 4). The ability to efficiently transform metabolic energy into speed is important for XC-skiing performance,[3,31] and previous studies have shown that beneficial technique modifications in XC-skiing improve skiing economy and performance.[25,32] An improved skiing economy in the present study is therefore expected to come from beneficial technique modification and thereby improve XC-skiing performance. However, no change was found in skiing economy during submaximal efforts during the intervention in any of the groups. Our intervention period might have been too short as changing skiing economy with technique modifications may take longer to develop in adolescent skiers.[33,34] Further, exercise intensity is an important factor in terms of how skiers cope with the G2 non-dominant technique in cross-country skiing, which skiers find more challenging at higher intensities.[20] This was also evident in the present study as the magnitude of the difference between sides increased as the speed increased (Table 4).

4.1 | Methodological considerations

The most effective movement pattern is not identical between XC-skiers, and therefore, technique modifications need to facilitate increased performance (or fewer injuries) to have relevance for the athlete. Therefore, performance changes should be monitored in studies on motor learning for athletes. However, although the performance of young athletes improves, this does not necessarily imply that learning or beneficial technique modification has occurred, because the physical capacity of young athletes develops rapidly.

A strength of the present study is that we were able to control for this when simultaneously testing the dominant side of the G2 technique. As there was no improvement on the dominant side, we propose that changes on the non-dominant side were due to improved technique and not just a change in physical capacity. However, in the present study, we assessed only knowledge-of-result; that is, the performance effects of the interventions. Future studies should assess the knowledge-of-performance; that is, using kinematical measures to detect whether the athletes changed their technical execution in response to the cues given during the intervention period.

In an applied practice setting, it was difficult to control the information the athletes gave each other in DYAD, or the thoughts of the athletes in VIDEO. There were three researchers involved in every training session in VIDEO and DYAD to control the practice setting, but the observations and dialogues were not recorded or formally analyzed in these groups. Even though all intervention groups used the same cue cards, the information received and the interpretation of this information by the athletes might therefore be different. Further, it could well be that the skiers were influenced by the coaching methods of their ordinary coaches in their skiing clubs.

A limitation of the present study is that testing was conducted in the laboratory, while the athletes performed the practice sessions outside on asphalt. It was not practically possible to train all athletes indoor due to the high number of athletes involved. Besides, doing so would have reduced ecological validity. Moreover, the data collection for cardiorespiratory and kinematic data (data not shown) required indoor testing. However, the athletes were familiarized with the treadmill, as seen in the absence of difference in performance from the last familiarization session to the pre-intervention main test session for the speed test (difference of 0.1 ± 1.1%). Further, rolling resistance has been found to be similar for treadmills and asphalt [35], and should not have affected the results in the present study.

We did not have a retention test, due to the advanced time-consuming performance tests and the large number of athletes. However, most of the athletes performed the post-testing session several days after the last practice session and the time from the last practice session to post-intervention test was balanced between groups. Further, a continuous motor skill task like the G2 technique is very well retained over long time intervals.[36]

We only asked the athletes one question relating to enjoyment and one question on self-perception of improved technique. Our questions may therefore have reduced validity and should be interpreted with caution.

5 | PERSPECTIVES

When timing, frequency, and amount of feedback are similar, coaching feedback from a competent coach seems superior in terms of combined performance, perceived enjoyment, self-perception of improved technique, and amount of self-practice performed compared with video feedback and dyad practice. However, video feedback with cue cards, filmed on the athletes' own smart phones, could be a valuable tool for coaches who want to increase individual feedback when coaching large groups or when the coach's sport-specific technique knowledge is limited. A combination of these feedback methods might be a good strategy. For dyad practice, the intervention period may have been too short and the preexisting sport-specific technique knowledge of the athletes too limited to be able to verify the potential benefits of this method. There was a large inter-individual variation in each group, and some athletes in each group were negatively affected. It should therefore be acknowledged that there might be individual preferences that should be taken into consideration when giving feedback, and as a coach, one might potentially degrade the level of technique in some athletes if attention is not paid to individual needs.

ACKNOWLEDGMENTS

The authors thank Magne Lund Hansen for his contribution during the intervention and Ola Eriksrud for valuable input to the manuscript.

CONFLICTS OF INTEREST

There are no conflicts of interest, including financial, consultant, institutional, or other relationships that might lead to bias or conflict of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

AUTHORS' CONTRIBUTIONS

OS, YO, and TL designed the study. OS, KH, CS, and TL performed the data collection. Data analysis was performed by OS, KH, and CS. OS, YO, and TL drafted the manuscript. All authors edited and revised the manuscript. All authors approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Ove Sollie https://orcid.org/0000-0003-4427-5164
Yngvar Ommundsen https://orcid.org/0000-0002-6500-8711
Thomas Losnegard https://orcid.org/0000-0001-8646-7477

REFERENCES

1. Bergeron MF, Mountjoy M, Armstrong N, et al. International olympic committee consensus statement on youth athletic development. *Br J Sports Med*. 2015;49(13):843-851.
2. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med*. 2004;34(7):465-485.
3. Losnegard T, Myklebust H, Spencer M, Hallen J. Seasonal variations in VO_{2max}, O_2-cost, O_2-deficit, and performance in elite cross-country skiers. *J Strength Cond Res*. 2013;27(7):1780-1790.
4. Lees A. Technique analysis in sports: a critical review. *J Sports Sci*. 2002;20(10):813-828.
5. van der Kamp J, Duivenvoorden J, Kok M, van Hilvoorde I. Motor skill learning in groups: some proposals for applying implicit learning and self-controlled feedback. *RICYDE Revista Internacional de Ciencias del Deporte*. 2015;11(39):33-47.
6. Ste-Marie DM, Law B, Rymal AM, Jenny O, Hall C, McCullagh P. Observation interventions for motor skill learning and performance: an applied model for the use of observation. *Int Rev Sport Exerc Psychol*. 2012;5(2):145-176.
7. Magill R, Anderson D. Augmented feedback. In. *Motor learning and control: concepts and applications*. 9th ed. New York: McGraw-Hill Publishing; 2011.
8. Porter JM, Wu W, Partridge JA. Focus of attention and verbal instructions: Strategies of elite track and field coaches and athletes. *Sport Sci Rev*. 2010;19(3-4):199-211.
9. Cumming J, Clark SE, Ste-Marie DM, McCullagh P, Hall C. The functions of observational learning questionnaire (FOLQ). *Psychol Sport Exerc*. 2005;6(5):517-537.
10. Shea CH, Wright DL, Wulf G, Whitacre C. Physical and observational practice afford unique learning opportunities. *J Mot Behav*. 2000;32(1):27-36.
11. Shea CH, Wulf G, Whitacre C. Enhancing training efficiency and effectiveness through the use of dyad training. *J Mot Behav*. 1999;31(2):119-125.
12. Lee TD, Swinnen SP, Serrien DJ. Cognitive effort and motor learning. *Quest*. 1994;46(3):328-344.
13. Nowels RG, Hewit JK. Improved learning in physical education through immediate video feedback. *Strategies*. 2018;31(6):5-9.
14. Williams AM, Davids K, Williams JG. *Visual Perception And Action In Sport*. E & FN Spon; 1999.
15. D'Innocenzo G, Gonzalez CC, Williams AM, Bishop DT. Looking to learn: the effects of visual guidance on observational learning of the golf swing. *PLoS One*. 2016;11(5):e0155442.
16. Kernodle MW, Carlton LG. Information feedback and the learning multiple-degree-of-freedom activities. *J Mot Behav*. 1992;24(2):187-196.
17. Janelle CM, Champenoy JD, Coombes SA, Mousseau MB. Mechanisms of attentional cueing during observational learning to facilitate motor skill acquisition. *J Sports Sci*. 2003;21(10):825-838.
18. Nilsson J, Tveit P, Eikrehagen O. Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomech*. 2004;3(1):85-107.
19. Stoggl T, Hebert-Losier K, Holmberg HC. Do anthropometrics, biomechanics, and laterality explain V1 side preference in skiers? *Med Sci Sports Exerc*. 2013;45(8):1569-1576.
20. Thorrud S. Is laterality, intensity or strength asymmetry associated with the preferred side in the G2 skating technique in cross-country skiing? [Master's thesis]. Levanger, Norway: North-Troendelag University College; 2013.
21. Losnegard T, Myklebust H, Hallen J. Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc*. 2012;44(4):673-681.
22. Stoggl T, Holmberg HC. Three-dimensional force and kinematic interactions in V1 skating at high speeds. *Med Sci Sports Exerc*. 2015;47(6):1232-1242.
23. Wulf G, Shea C, Lewthwaite R. Motor skill learning and performance: a review of influential factors. *Med Educ*. 2010;44(1):75-84.
24. Wulf G, Lewthwaite R. Optimizing performance through intrinsic motivation and attention for learning: the OPTIMAL theory of motor learning. *Psychon Bull Rev*. 2016;23(5):1382-1414.
25. Losnegard T, Tosterud OK, Troen E, Carlsen CH, Paulsen G, Rud B. The influence of pole lengths on O2-cost, kinematics, and performance in double poling at high speeds before and after a training period with long poles. *Eur J Appl Physiol*. 2019;119(11-12):2579-2587.
26. Cohen J. *Statistical power analysis for the social sciences*. 2nd ed. New York: Routledge; 1988.
27. Dunn OJ. Multiple comparisons using rank sums. *Technometrics*. 1964;6(3):241-252.
28. Ericsson KA, Krampe RT, Teschromer C. The role of deliberate practice in the acquisition of expert performance. *Psychol Rev*. 1993;100(3):363-406.
29. Knoblich G, Flach R. Predicting the effects of actions: interactions of perception and action. *Psychol Sci*. 2001;12(6):467-472.
30. Mueller D, Georges A, Vaslow D. Cooperative learning as applied to resident instruction in radiology reporting. *Acad Radiol*. 2007;14(12):1577-1583.
31. Sandbakk O, Holmberg HC, Leirdal S, Ettema G. Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *Eur J Appl Physiol*. 2010;109(3):473-481.
32. Losnegard T, Myklebust H, Ehrhardt A, Hallen J. Kinematical analysis of the V2 ski skating technique: a longitudinal study. *J Sports Sci*. 2017;35(12):1219-1227.
33. Zoppirolli C, Modena R, Fornasiero A, et al. Talent development in young cross-country skiers: longitudinal analysis of anthropometric and physiological characteristics. *Frontiers in Sports and Active Living*. 2020;2:111.

34. Skattebo O, Hallen J, Ronnestad BR, Losnegard T. Upper body heavy strength training does not affect performance in junior female cross-country skiers. *Scand J Med Sci Sports*. 2016;26(9):1007-1016.
35. Gloersen O, Losnegard T, Malthe-Sorenssen A, Dysthe DK, Gilgien M. Propulsive power in cross-country skiing: application and limitations of a novel wearable sensor-based method during roller skiing. *Front Physiol*. 2018;9:1631.
36. Schmidt RA, Lee TD, Winstein C, Wulf G, Zelaznik HN. Retention and transfer. *Motor control and learning: a behavioral emphasis*. 6th ed. (pp. 408). Champaign IL: Human Kinetics; 2018.

How to cite this article: Sollie O, Holmsen K, Steinbo C, Ommundsen Y, Losnegard T. Observational vs coaching feedback on non-dominant whole-body motor skill performance—application to technique training. *Scand J Med Sci Sports*. 2021;00:1–12. https://doi.org/10.1111/sms.14030

Ove Hukset Sollie // Determinants of performance in male and female adolescent competitive cross-country skiers