Doctor Philosophiae // No. 6 – 2022

Training and pole length manipulation for optimizing physiological capacities and technique to improve performance in Long-distance and Olympic-distance cross-country skiing

Per-Øyvind Torvik

THE FACULTY OF EDUCATION AND ARTS

NORD
University

www.nord.no

Training and pole length manipulation for optimizing physiological capacities and technique to improve performance in Long-distance and Olympic-distance cross-country skiing

Per-Øyvind Torvik

Doctor Philosophiae
The Faculty of Education and Arts
Nord University

Per-Øyvind Torvik

Training and pole length manipulation for optimizing physiological capacities and technique to improve performance in Long-distance and Olympic-distance cross-country skiing

Doctor Philosophiae no. 6 (2022)

ISBN: 978-82-93196-55-6

Print: Trykkeriet, Nord University

www.nord.no

Abstract

Modern cross-country (XC) skiing is an endurance winter sport divided into the three disciplines of sprint (800-1800 m), distance skiing (5-50 km) and long-distance skiing (40-220 km). XC skiers engage large muscle groups of the upper and lower limbs to different extents when employing the 11 sub-techniques to ski effectively across hilly snow-covered terrain. Over the last decades, racing speed has increased substantially, partly due to more effective use of the upper body, the development of more effective double poling and G3 sub-techniques, and more frequently used classic double poling and skating G3 sub-techniques in all types of terrain. Accordingly, the training routines for development of performance in XC skiing are aided by concurrent improvements in the skier's physiological capacity, skiing technique and pole length manipulations. A consequence of the different competition formats and distances is more specialized training to develop cross-country skiers' performance by specializing in sprint, distance in the Olympic and long-distance disciplines. Furthermore, pole length manipulations may have enhanced performance in both Olympic distance skiers (ODS) and long-distance skiers (LDS). The overall objective of this thesis is to examine training characteristics and pole length manipulation for optimizing performance and associated physiological and kinematical capacities in long-distance and Olympic-distance XC skiing.

In order to answer the overall objective, the two specific aims were 1) to compare physiological capacities, and kinematical patterns in double poling (DP) between Olympic distance and long-distance XC skiers, and analyze the training characteristics of long-distance XC skiers (Studies I-II), and 2) to describe choice of pole lengths among competitive XC skiers and evaluate the effects of pole length manipulation on performance in classical and skating style XC skiing (Studies III-VI).

Study I showed that, compared to ODS, LDS displayed higher double poling (DP) peak oxygen uptake (DP-VO_{2peak}) (68.3±2.1 versus 65.1±2.7 $ml \cdot kg^{-1} \cdot min^{-1}$, $p=0.050$), also relative to running maximal oxygen uptake (97% versus 94%, $p=0.075$), higher gross efficiency (GE) (17.2% versus 15.9%, $p=0.029$), and higher peak speed (+1.4±0.2 $km \cdot h^{-1}$, $p=0.030$). There were no group differences in cycle length (6.0±0.7 m versus 5.7±0.6 m, $p=0.503$, $g_s=0.39$) or cycle rate (1.12±0.18 Hz versus 1.04±0.08 Hz, $p=0.385$, $g_s=0.58$) at any speed in DP, although LDS displayed longer relative poling times (~2.4 percentage points) at most speeds compared to ODS ($p=0.015$). Also found were group versus speed interaction effects ($p<0.05$) for pole angle

and vertical fluctuation of body center of mass (CoM), with LDS maintaining a more upright body position, more vertical pole angles at touchdown and lift-off and for the distance between pole tip and feet at touchdown (longer distance for LDS), and the LDS seemed better able to maintain these characteristics at higher speeds.

ODS displayed consistently slightly higher normalized electromyography ($nEMG_{avg}$) amplitudes than LDS in the rectus abdominis ($p=0.074$) and biceps femoris muscles ($p=0.027$). DP speed affected $nEMG_{avg}$ of most muscles ($p<0.001$, but less so for triceps brachii ($p=0.202$), erector spinae ($p=0.177$) and rectus femoris ($p=0.620$). $nEMG_{avg}$ showed a particular increase at speeds above 18 $km \cdot h^{-1}$. LDS performed slightly better on 1RM upper-body strength (122 versus 114 kg, $p=0.198$), with no group differences in power in the pull-down exercise.

Study II demonstrates the training characteristics of world-class LDS, consisting of high volumes (861±90 h annually) with 88.7% low-intensity, 6.4% moderate-intensity and 4.8% high-intensity endurance training and 50-60% of this training using the DP technique. LDS performed long but few sessions in a pyramidal intensity distribution pattern (when compared to previous literature on ODS). LDS performed. Accordingly, the training characteristics match the specific demands of long-distance skiing, with competitions typically performed as long-duration DP. Additionally, the LDS designed training sessions to copy the demands that they meet in e.g., the most acknowledged long distance races Vasaloppet or Marcialonga.

Studies III-V showed that performance in XC skiing can be improved by increasing pole length in the main XC skiing sub-techniques. In DP and G3 skating, long poles led to 2.6% and 2.7% lower oxygen cost compared to self-chosen poles, respectively. In G3 skating, long poles also showed 2.1-4.1% higher GE, and in DP, longer poles increased time to exhaustion (TTE) by 40 seconds (i.e. 9.5% improvement). During an on-snow skating competition, longer poles led to better performance (7.1 seconds) compared to self-chosen poles (all $p>0.05$), with longer poles seemingly most beneficial in uphill terrain.

When analyzed within each sex (**Study VI**), a moderate correlation between sprint FIS points and body-height-normalized pole length in both skating ($r=0.36$, $p=0.030$) and classical techniques ($r=0.43$, $p=0.008$) was found in women. This coincides with the use of classical ski poles of maximum length under the current regulations, which was most pronounced for men, while both sexes used skating poles similar to the recommendations given by the equipment industry.

In conclusion, this thesis provides novel information about the physiological and technical differences between ODS and LDS and the sport-specific training characteristics of world-class LDS. Here, Study I found the highest ever reported upper body-leg peak oxygen uptake ratio (DP/RUN-VO_{2peak} ratio) of 97% in LDS, which coincided with better DP performance and ability to maintain effective technique at faster DP speeds. In addition, LDS achieved higher GE than ODS and demonstrated longer relative poling times and lower normalized EMG amplitudes in rectus abdominis and biceps femoris. The main reasons for these advantages in DP performance and physiology are probably associated with the unique training patterns described in Study II. Here, the data showed that the superior DP performance of world-class long-distance XC skiers was followed by high annual training volumes with most training performed as low-intensity training. However, some apparent format-specific differences in training compared to previous literature on ODS are present: LDS train longer but fewer sessions (i.e. regular 3-5 h sessions), use a pyramidal intensity distribution pattern (i.e. 88.7% low-intensity training (LIT), 6.4% moderate-intensity training (MIT) and 4.8% high-intensity training (HIT) and spend more of their training time on the DP technique (50-60%). Accordingly, the training routines seem to match the specific demands of long-distance XC skiing, with competitions commonly performed as long-duration DP. Taken together, the combination of better DP-specific aerobic energy delivery capacity, strength, efficiency and technical solutions that provide the superior DP performance found among specialized LDS are reflected in their training routines with a strong focus on DP training specifically for long-distance events.

Studies III-VI aimed to describe the choice of pole length among competitive XC skiers and evaluate the effects of pole length manipulation on performance in the classical and skating style. All studies showed longer poles to be superior to self-selected and shorter poles, both in DP (Study III) and G3 skating (Study IV) when roller skiing and when ski skating on snow (Study V) and in classic sprint racing for women (study VI). Performance benefits of increased pole length seem to be most prominent in uphill terrain sections and associated with altered kinematics, reduced vertical displacement of CoM and reduced oxygen cost. While these benefits have previously been demonstrated for DP on flat to moderate inclines, Paper III was the first study to show the benefits of longer poles for DP on uphill terrain, although diagonal stride was the superior technique here. Another novel finding was the superior effect of longer than self-selected pole length in G3 skating on performance and GE in uphill and at high speed with lower inclination, which was associated with a greater knee angle in the lowest position, suggesting that skiers have less vertical displacement when using long poles. Also, during on-snow ski skating, longer poles were beneficial for female skiers. Here, the performance improvement induced by longer poles occurred in the initial part of the race and the longest uphill section, which coincided with more use of the G3 sub-technique than G2. Since this occurred without any changes in physiological parameters, but with improved perceived ski-feeling and lower ratings of perceived exertion with long poles, it is suggested that the positive effects of choosing longer poles are followed by the same effective mechanisms as those found for DP and G3 skating. This is also supported by Study VI, which reports that the best-performing male and female XC skiers use as long classic ski poles as possible under the current regulations. In skating, similar body-height-normalized pole lengths are used by men and women, similar to those recommended by the industry.

Summary in Norwegian

Moderne langrenn er en fysisk og teknisk krevende vinteridrett som kan deles inn i tre disipliner; sprint (1000-1800 m), Olympisk distanselangrenn (5-50 km) og langløp (turrenn fra 40-220 km). I langrenn kombinerer utøverne overkroppen og beina for å bevege seg så effektivt som mulig i varierende terreng, hastigheter og skiføre ved hjelp av å veksle mellom 11 delteknikker i klassisk og skøyting. Hastigheten i langrenn har økt betydelig de to siste tiårene, noe som delvis kan forklares av bedre utnyttelse av overkroppen og mer effektiv staketeknikk i klassisk og dobbeltdans-teknikk i skøyting – to teknikker som brukes stadig mer. En konsekvens av denne utviklingen er at utøvere stadig må være på jakt etter å utvikle sin fysiske kapasitet, teknikk og utstyr. Arbeidskravene i de forskjellige konkurransedisiplinene har ført til en økt spesialisering innen sprint, distanse og langdistanse. Videre har man både i de Olympiske disipliner og langløp eksperimentert med stavlengder for å forbedre prestasjonen. Basert på dette har hovedhensikten med denne avhandlinga vært å analysere treningsinnhold, manipulering av stavlengder for å optimalisere prestasjon og tilhørende fysiologiske og tekniske kapasiteter hos langrennsløpere som konkurrerer i langløp (LDS) og Olympisk-distanselangrenn (ODS).

Dette ble undersøkt gjennom følgende problemstillinger; 1) sammenligne fysiologiske kapasiteter og tekniske bevegelsesmønstre i staking mellom ODS og LDS, og analysere treningen til verdens beste LDS (studie I og II), og 2) beskrive valg av stavlengder hos aktive olympiske langrennsløpere og evaluere effekten av stavlengde-manipulering på langrennsprestasjon i klassisk og skøyting (Studie III-VI).

Resultatene fra **Studie I** viste at LDS hadde et høyere peak oksygenopptak i staking (DP-VO_{2peak}) (68.3±2.1 versus 65.1±2.7 $ml \cdot kg^{-1} \cdot min^{-1}$, $p=0.050$), høyere VO_{2peak} relativt til maksimalt oksygenopptak i løping (henholdsvis 97% vs 94%, $p=0.075$, $g_s=1.08$), høyere effektivitet (17.2% vs 15.9%, $p=0.029$), og oppnådde høyere maksimal hastighet i staking ($+1.4 \pm 0.2$ $km \cdot t^{-1}$, $p=0.030$) sammenlignet med ODS i en prestasjonstest til utmattelse i staking.

Det ble ikke funnet gruppeforskjeller i sykluslengde (6.0±0.7 m versus 5.7±0.6 m, $p=0.503$, $g_s=0.39$) eller syklusfrekvens (1.12±0.18 Hz versus 1.04±0.08 Hz, $p=0.385$, $g_s=0.58$) i staking. LDS viste en lengre relativ anvendt tid i selve stavtaket (~2.4%-poeng) på de fleste hastigheter sammenlignet med ODS ($p=0.015$), og vi fant en gruppe versus hastighet interaksjon ($p<0.05$) på stavvinkel og vertikal forflytning av kroppens tyngdepunkt, der LDS i større hastighet holdt

kroppen i en mer oppreist posisjon, hadde stavisettet lengre foran bindingen og mer vertikal stavvinkel i avslutningen av stavtaket.

ODS hadde generelt noe høyere normalisert EMG aktivitet enn LDS i de rette magemusklene ($p=0.074$) og den tohodede knebøyeren ($p=0.027$). Hastighet i staking påvirket $nEMG_{avg}$ i de fleste muskler ($p<0.001$, men mindre for triceps brachii ($p=0.202$), erector spinae ($p=0.177$) og rectus femoris ($p=0.620$). $nEMG_{avg}$ økte spesielt ved hastigheter over 18 $km \cdot t^{-1}$. LDS var også litt sterkere (122 versus 114 kg, $p=0.198$) i overkroppsstyrke (1RM nedtrekk foran kroppen).

Studie II. Treningen til LDS besto av et høyt årlig treningsvolum (861±90 timer) der utholdenhetstreningen var fordelt som 88.7% lavintensitets trening, 6.4% moderatintensitets trening og 4.8% høyintensitets trening og hele 50-60 % av treningsvolumet var staking. LDS gjennomførte færre, men lengre økter (3-5 t) og hadde en mer pyramidal intensitetsdistribusjon (sammenlignet med tidligere studier på ODS). Derfor kan vi si at LDS gjennomfører både et totalt treningsinnhold og designer økter som møter de spesifikke kravene de for eksempel møter i Vasaloppet eller Marcialonga.

Studie III-V viste at lengre staver både i klassisk og skøyting forbedret prestasjonen i de viktigste delteknikkene. I staking og dobbeltdans førte lengre staver (sammenlignet med selvvalgte og kortere staver) til signifikant forbedret arbeidsøkonomi og høyere hastighet, spesielt i motbakkene, mens lengre staver i staking førte til økt effektivitet og bedre total prestasjon (alle $p>0.05$).

Når valg av stavlengder ble undersøkt innad i begge kjønn (**Studie VI**), var det en moderat korrelasjon mellom FIS poeng i sprintlangrenn og stavlengde normalisert for kroppshøyde i både skøyting ($r=0.36$, $p=0.030$) og klassisk teknikk ($r=0.43$, $p=0.008$) hos kvinner. Dette viser at utøverne brukte så lange klassiske skistaver som mulig innenfor gjeldende regelverk, at menn valgte noe lengre klassiskstaver (relativt til kroppshøyden), mens begge kjønn brukte skøytestaver tilsvarende anbefalinger gitt av utstyrsbransjen.

Oppsummert gir disse studiene ny informasjon om forskjeller i fysiologiske, tekniske og idrettsspesifikke treningskarakteristikker mellom LDS og ODS.

Studie I viser at LDS oppnådde den høyeste rapporterte VO_{2peak} /VO_{2maks} ratioen mellom staking og løp vi kjenner i forskningslitteraturen i dag. Dette er med på å forklare deres bedre stakeprestasjon og evne til å opprettholde en effektiv staketeknikk i større sammenlignet med

ODS. I tillegg hadde LDS bedre arbeidsøkonomi enn ODS og lengre staketid (den delen av stakesyklusen hvor stavene er i bakken). Videre ble det målt lavere normalisert EMG i rectus abdominis og biceps femoris på en standard submaksimal belastning. Hovedårsaken til bedre prestasjon i staking og høyere fysiologiske kapasitetene hos LDS er sannsynligvis knyttet til deres unike treningsinnhold som er undersøkt i studie II. LDS gjennomførte et høyt årlig treningsvolum, med mye lavintensiv utholdenhetstrening etter en pyramidal intensitetsdistribusjon som står i motsetning til tidligere litteratur rapportert for ODS som benytter har mer polarisert distribusjon av utholdenhetstreningen. LDS trente også færre, men lengre treningsøkter per uke (jevnlig økter på 3-5 timer) sammenlignet med litteratur på ODS, og de trente spesifikk staking i hele 50-60% av det totale treningsvolumet sammenlignet med 15-20% hos ODS.

Treningsrutinene til LDS ser derfor ut til å samsvare godt med de spesifikke kravene som stilles i langløp som vanligvis gjennomføres som staking over lange distanser. Samlet sett gjenspeiles kombinasjonen av god aerob energileveranse, effektivitet og gode tekniske løsninger i staking i treningsrutinene som har stort fokus på spesifikk staketrening for langløp.

Studie III-VI indikerte at lengre staver var bedre sammenlignet med selvvalgte og korte staver, både i staking (studie III), dobbeldans på rulleski (studie IV), skøyting på snø (Studie V) og i klassisk sprintlangrenn for damer (studie VI). Spesielt ser det ut til at lengre staver forbedret prestasjonen i motbakke, noe som ble assosiert med tekniske endringer som redusert vertikal forflytning av kroppens tyngdepunkt og redusert oksygenkostnad. Slike fordeler med lengre staver har tidligere blitt vist i lett terreng, mens studie III var den første til å dokumentere dette i bratte motbakker, selv om diagonalgang på rulleski likevel var den mest effektive teknikken her. Et annet funn var fordelen med lengre staver i skøyting dobbeltdans både i motbakker og i høy fart i lettere terreng. Disse funnene var assosiert med en større vinkel i kneleddet ved laveste posisjon og dermed en mindre vertikal opp og ned bevegelse av tyngdepunktet. Fordelene med lengre staver ble også vist hos kvinner i en simulert skøytekonkurranse på snø (studie V). Her bedret prestasjon seg som et resultat av lengre staver i den første delen av løypa og i løypas lengste stigning der dobbeltdans og padling ble benyttet.

I tillegg brukte utøverne mer dobbeldans når de gikk med lengre staver. Siden dette skjedde uten endringer av fysiologiske parametere, men med en forbedret teknisk følelse og lavere subjektiv oppfatning av anstrengelse (Borg skala), antar man at de positive effektene av å bruke lengre staver kommer fra de effektive mekanismer som tidligere er beskrevet for staking og dobbeldans. Dette er også støttet av studie VI som viser at de best presterende menn og kvinner i klassisk langrenn bruker så lange staver som mulig i henhold til regelverket. I skøyting blir like lange kroppshøyde normaliserte staver brukt av både kvinner og menn, og det er stavlengder som følger anbefalinger gitt av utstyrsindustrien.

Acknowledgments

This work has been carried out in my spare time, late evenings, early mornings, and holidays. However, my employers, Nord University and Meråker Videregående Skole, have facilitated and enabled me to do the work in the Department of Sports Science and Physical Education, Nord University, Levanger and Meråker have provided me with two expert supervisors from Nord University and the Centre for Elite Sports Research, Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology.

First to my former student and current supervisor, Professor Øyvind Sandbakk, for guiding and encouraging me through the process. Thanks for your contributions, with your knowledge, experience, and expertise as a XC skier, scientist and discussion partner. I am deeply grateful for your competent ability to give feedback on "every line" in the manuscript. Throughout the process, you had a total overview and helped me keep a clear structure. Thanks for your inspiration, motivation and personal support. Thanks, Øyvind, for your constant and never-ending demands for improvement in the articles and this manuscript. Finally, thanks for letting me have the applied perspective as a practitioner in XC skiing in this work. I introduced you to the field of exercise physiology and watched you "grow over my head", and now you are lifting me up to your "level".

To Roland van den Tillaar, my second supervisor, thanks for exceptional help with the statistics and your valuable contribution to writing the articles and supervising the manuscript. Thanks, Roland, for your patience with my writing and spelling. Thanks for whetting my research appetite and allowing me to study sport, exercise and science further.

To Jørgen Danielsen, Rune Kjøsen Talsnes, Guro Strøm Solli, Boye Welde, Erna von Heimburg, Johan Persson, Torkel Sende, Guro Bostad, the co-authors of my papers who contributed to constructing the six articles in this thesis.

To Rolf Bøen, Alex Wisnes and Jan Helgerud for introducing me to sports science and exercise physiology. To Alex for creating the interest in exercise physiology through his exciting and excellent lectures. To Jan for introducing me to the field of science in the topic. I am deeply grateful to Rolf for helping me choose a career and pushing me in an academic direction.

To my colleagues and friends at the Department of Sports Science and Physical Education, Nord University and Meråker Videregående Skole, for their essential support. Thanks for all

the constructive, sound and sometimes intense discussions on sport science and XC skiing. Our ongoing efforts to find better ways to develop young XC skiers' endurance, strength and technique to become world-class skiers has inspired and motivated me to write this thesis.

Special thanks to Kjell Olav Strømsøyen and Ole Morten Iversen for employing me and taking me under your wings as a young, inexperienced cross-country coach, teaching me the "*Meråker model*", and giving me responsibility and companionship to develop as a teacher and coach, which led to this thesis.

To Ove Erik Tronvoll, my closest colleague throughout recent years, who had to put up with me when I combined my work on this thesis with work at the Department of Sports Science and Physical Education. Thanks for responding to all my daily questions, being a useful discussion partner and asking many questions to add depth and knowledge to my and our work. Thanks also for proofreading some manuscripts in this thesis and our daily work.

To Rune Kjøsen Talsnes and Guro Strøm Solli, my colleagues in Meråker and in our research group (PULS), thanks for always giving a helping hand, proof reading and your constructive discussions have made valuable contributions to the manuscript. Thanks for giving me criticism and inspiring me to continue to finish my degree in a reasonable time.

To Johan Persson, Ove Erik Tronvoll, Rune Kjøsen Talsnes and Jonatan Engdal, who have been skillfully running our endurance laboratory in Meråker. Your careful and accurate work has made our laboratory suitable for high-quality studies within exercise physiology. Thanks for providing both high quality and high spirits in the lab.

To the volunteers and cross-country skiers who have contributed with their work, time, and efforts to the data in this thesis, I wish to express my deepest gratitude.

To my parents, Unni and Øyvind Torvik, for helping me through the "hard" years of primary and secondary school, and encouraging and motivating me to take an education instead of investing my future in the family farm. Thanks for letting me follow my own dreams.

To Bjørg, my lovely wife, thanks for your love, patience, generosity and encouragement. Thanks for being my supervisor in life, for our everyday life and for keeping me sane over the past months. But most of all, thanks for being my best friend; I owe you everything and I see the sacrifices you have made to help me get to this point.

To Morten and Truls, my beloved sons who make me proud every day, as they have chosen a similar path in life to myself, dedicating themselves to helping people achieve their goals in life as professional sports instructors in healthcare and schools.

Nobody can achieve anything alone and without such a team behind me, I would have been unable to finish this project. I therefore wish to express my warmest gratitude.

List of Publications

This thesis is based on the following six articles, which will be referred to in the manuscript by their Roman numerals. The articles are copied with permission from the journals where they were published.

I. **Torvik P-Ø.,** van den Tillaar R., Talsnes R., Sandbakk Ø., & Danielsen J. (2022). A comparison of the biomechanical and physiological responses to double poling between long-distance specialists and all-round distance cross-country skiers. *Accepted Front. Sports Act. Living - Elite Sports and Performance Enhancement.*

   Authors contribution: *Torvik and Sandbakk planned and designed the study. Torvik, Danielsen and Tillaar performed the data collection. Danielsen processed and presented the kinematic data, while Tillaar analyzed and visualized the EMG data. Torvik, Talsnes and Sandbakk analyzed and presented the remaining data. All authors authored and finalized the manuscript for publication. All authors contributed to the revision and approved the final article.*

II. **Torvik, P-Ø**., Solli, G. S., & Sandbakk, Ø. (2021). The training characteristics of world-class male long-distance cross-country skiers. *Frontiers in Sports and Active Living*, *3*, 20.

   Authors contribution: *Torvik and Sandbakk planned and designed the study. Torvik, Solli and Sandbakk performed the data collection. Torvik, Solli and Sandbakk performed the methodology, analyzed and presented the data. All authors authored and finalized the manuscript for publication. All authors contributed to the revision and approved the final article.*

III. **Torvik, P-Ø**., Persson, J., & van den Tillaar, R. (2021). The Effects of Sub-Technique and Pole Length on Classic Roller Skiing Performance and Physiological Responses at Steep Uphill Inclination. *Journal of Human Kinetics*, *77*(1), 97-105.

   Authors contribution: *Torvik and Persson planned and designed the study. Torvik, and Persson performed the data collection. Torvik, Persson and Tillaar performed the methodology, analyzed and presented the data. Torvik and Tillaar authored and finalized the manuscript for publication. All authors contributed to the revision and approved the final article.*

IV. **Torvik, P-Ø**., Heimburg, E. D. V., Sende, T., & Welde, B. (2019). The effect of pole length on physiological and perceptual responses during G3 roller ski skating on uphill terrain. *Plos One*, *14*(2), e0211550.II.

Authors contribution: *Torvik, Sende, Heimburg and Welde planned and designed the study. Torvik, Sende and Welde performed the data collection. Torvik, Sende, Heimburg and Welde performed the methodology, analyzed and presented the data. Torvik, Heimburg and Welde authored and finalized the manuscript for publication. All authors contributed to the revision and approved the final article.*

V. **Torvik, P-Ø**., van den Tillaar, R., Bostad, G., & Sandbakk, Ø. **(**2021**).** Pole Length Influences Performance During On-Snow Skating in Female Cross-Country Skiers. *Journal of Science in Sport and Exercise* doi:10.1007/s42978-021-00134-0

Authors contribution: *Torvik and Bostad planned and designed the study. Torvik and Bostad performed the data collection. Torvik, Tillaar and Sandbakk performed the methodology. Tillaar analyzed and presented the data. All authors authored and finalized the manuscript for publication. Torvik contributed to the revision and approved the final article.*

VI. **Torvik, P-Ø**., van den Tillaar, R., Sandbakk, Ø. (2021). Choice of pole and ski lengths among elite cross-country skiers: the influence of sex and performance level. *Frontiers in Sports and Active Living* 3:654864. doi: 10.3389/fspor.2021.654864

Authors contribution: *Torvik and Sandbakk planned and designed the study. Torvik performed the data collection. Tillaar, Torvik and Sandbakk performed the methodology, analyzed and presented the data. All authors authored and finalized the manuscript for publication. All authors contributed to the revision and approved the final article.*

Abbreviations

ANOVA – Analysis of variance
BMI – Body mass index
CMRR - Common-mode rejection ratio
CoM – Body center of mass
CO_2 – Carbon dioxide
CP – Competition period
DP – Double poling
DP-VO_{2peak}/RUN-VO_{2max} – Ratio between double-poling peak oxygen uptake and running maximal oxygen uptake
EMG – Electromyography
$nEMG_{avg}$ - Cycle average normalized EMG amplitude
FIS – International Ski Federation
GE – Gross efficiency
g_s – Hedges' g_s
G1-5 –sub-techniques (gears) in skating
GP – General preparation period
GPS – Global positioning system
HIT – High-intensity training
HR – Heart rate
HR_{max} – Maximal heart rate
Hz – Hertz (unit of frequency)
IQR – Interquartile range
[La-] – Blood lactate levels
LDS – Long-distance skiers
LMM – Linear mixed model
LIT – Low-intensity training
mmHg – millimeters of mercury (manometric unit of atmospheric pressure)
MIT – Moderate-intensity training
Pic/sec – Pixels per second
RER – Respiratory exchange ratio
RMS – Root-mean-square
RoM – Range of motion
RPE – Rating of perceived exertion
SD – Standard deviation
SS – self-selected poles
SP – Specific preparation period
TTE – Time to exhaustion
VCO_2 – Volume of carbon dioxide
VO_{2max} – Maximal oxygen uptake
VO_{2peak} – Peak oxygen uptake
VSC – Visma Ski Classics
XC – Cross-country
µL – microliter
3D – Three dimensional
2D – Two dimensional

Contents

Figure 1: Illustration of modern cross-country skiing and research projects

Chapter 1: Introduction

Competitive cross-country (XC) skiing is one of the most demanding winter endurance sports, including whole-body locomotion performed over varying terrain in skating and classical styles, leading to constant alternations in speed, work rate and metabolic intensity [1]. Skiers compete in the sprint, distance and long-distance skiing formats, with races lasting from 3 min in sprints to 4-5 hours for long-distance, at altitudes ranging from sea level to 1800 m above sea level [2]. Although track profiles are standardized by the International Ski Federation (FIS), snow conditions, track preparation, ski wax, temperatures and weather conditions also influence skiers' speed throughout the track [2]. Accordingly, skiers must adapt their equipment, such as skis and poles, to the conditions within the competition rules.

XC skiers must therefore adapt their training to meet the competitive demands and develop the main performance-determining variables. In XC skiing, aerobic endurance is regarded as the main determinant [3-9], supplemented by adequate anaerobic capacity [6, 10-15]. The single best predictor of aerobic performance in XC skiing is maximal oxygen uptake (VO_{2max}), and previous reports show values >6 $L\cdot min^{-1}$or 80-90 $ml\cdot min^{-1}\cdot kg^{-1}$ in successful male XC skiers, with approximately 10-15% lower body-mass normalized values in women [1, 16]. Common to world-class performance in all three formats are high sport-specific peak oxygen uptakes (VO_{2peak}) [14], the ability to rapidly adapt to changes in metabolic requirement, the capability to sustain a high metabolic anaerobic energy turnover [11, 12, 14, 15, 17] to tolerate the high work rates in uphill sections and maintain high skiing efficiency [1, 2, 14, 15]. Further, the ability to utilize a high proportion of VO_{2max} and achieve an efficient skiing technique in the different sub-techniques is regarded as crucial for performance in this complex locomotion [18-20]. Furthermore, sufficient muscle strength [2, 21], maximal skiing speed ability (V_{max}) [22], and well-developed pacing strategies [2, 8, 23-29] will decide who wins competitions. Crucial for success in mass starts is also the tactical ability to draft behind other competitors effectively trough out the course [30] gain a good position before the final spurt starts and to have high sport-specific V_{max} to decide the competition [22]. Finally, the choice of skis and poles influences performance outcome, and research has showed that particularly pole lengths [31-37] ski, grinding and wax [38] play major roles.

While sprint and distance XC skiers' physiological capacities and performance have been widely investigated and described [1, 2, 4, 6, 8, 14, 24, 39-41], only a few studies have described the physiological capacities and technical abilities of Long Distance Skiers (LDS) [42-45]. In addition, training of LDS has not yet been examined.

Modern XC skiing history (1980 to date)

XC skiing was first introduced as an Olympic sport in Chamonix in 1924. The competitions were only performed in the classical style, and diagonal stride, double poling with a kick and double poling were the dominant sub-techniques until the mid-1980s. The development of the skating style started in the early 1980s and skating immediately outperformed the classic skiing style [46]. The future of classical skiing was widely discussed, and in 1988, the International Ski Federation (FIS) decided to divide competitions into two styles, classic and skating. Later studies have shown skating to be 9-11% faster than classical skiing [47].

The skating technique was established with five different sub- techniques and was operated as a gear system (G1-5) used in different terrains and speeds [18, 48]. With the introduction of skating in XC skiing, skating-specific skis, bindings, boots, and poles were developed and adapted for this style. Skating skis were 10-20 cm shorter and were customized to the skating technique. Bindings were more stable and stiffer, and boots were higher and more stable. Pole length increased and a standard of skating poles 10 cm longer than classic poles was established [46].

The competition program is also developed during this period. In the 1984 Olympics, it contained four disciplines for both women and men, with distances ranging from 5 to 50 km, with three individual time-trial races and a 4 x 5/10 km relay, all in the classical style. The 2022 Olympic Games contained six competitions, five of which were mass starts ranging from 1.3 km sprint races to 50 km, lasting from ~3 minutes to ~2 h [49], and a 50/50% distribution of classic and skating. Improvements in skiing equipment, track and ski preparation, changes in track characteristics and specialized training preparations have contributed to a ~10% higher speed from 1992 until 2018 [14]. Moreover, the introduction of the sprint discipline in the late 1990s led to an even higher speed requirement in XC skiing.

Another major development in XC skiing is the capacity for double poling (DP), which has greatly improved upper body physiology and DP technique. A consequence of this development was that the 90 km Vasaloppet in 2005, for the first time was completed by using only DP and performing at a high level, which started a DP revolution in XC skiing. Gradually, long-distance XC skiers adapted their training by specializing in DP which allowed them to perform long-distance races solely in DP, even in tracks with relatively long, demanding uphills. However, this no longer only applies to elite skiers but is prevalent among the top 1000 ranked skiers in long-distance evens [50]. The same pattern was also seen in ODS, with increasing use of DP until 2014, when both male and female XC distance skiers successfully employed DP over entire FIS-standardized tracks when using skis without kick wax, longer poles and by running herringbone in the steepest uphills. Slower speed in the steepest uphills was compensated by higher speeds in all other terrain, resulting in a higher average speed. However, when the DP technique seemed to be outperforming the traditional classical techniques (diagonal and DP with kick), FIS regulated the pole length (<83% of body height) and introduced DP free zones in suitable uphills from 2016 [51]. These regulations have preserved the diagonal stride as a competition sub-technique in distance XC races, while long-distance races are performed almost exclusively using the DP sub-technique.

The development and increased popularity of long-distance races made them an alternative to the distance races in the World Cup, and the Visma Ski Classics, including races like Vasaloppet, Birkebeineren and Marcialonga, have achieved a high status for athletes, sponsors, the media and spectators.

Developments in XC skiing over the last two decades include the way strength and endurance training are executed in XC skiing for specialized sprinters, distance and long-distance XC skiers. All the above-mentioned changes have focused more on strength and endurance training of the upper body, and the importance of a well-developed upper body for performance has been shown for all XC disciplines [52]. Therefore, the G3 and DP sub-techniques, where the upper body is a particularly important contributor to propulsion, have become more widely used in all three competition formats [14].

Few skiers nowadays can perform in all three competition formats in one season due to the differences in competition demands, including energy systems in use and technical skills required to succeed. In recent decades, only a few male skiers in the World Cup were among the top-ranked in both distance and sprint events, while this pattern is less pronounced in women, which may be related to more similar demands in sprint and distance skiing for the women [14]. Overall, today’s athletes are more specialized and optimize their training to perform in skating or classic technique or in one or two of the competition formats.

Competitive and physiological demands in Olympic distance skiing and Long-distance skiing

The complexity of XC skiing requires athletes to master a wide range of physiological demands in both Olympic and Long-distance races. Olympic competitions range from 1.3 km to 50 km and last from ~3 min to more than two hours. The track consists of approximately 1/3 flat, 1/3 uphill, and 1/3 downhill terrain [51]. Uphills are the most discriminating terrain, with more than 50% of race time spent there [7, 18, 47]. However, the better skiers are also faster in the remaining flat and downhill sections, where about 35% and 15% respectively of race time are spent. The terrain varies from -20% to 20% in inclination with speed ranging from 5-70 km·h^{-1} [2]. Further, a specific segment in the course (flat, downhill or uphill) takes from 10-35 s to ski and is rarely longer than 70 s in a FIS-standardized track [14]. Unlike in all other endurance sports, these substantial variations lead to around 25 transitions in sub-technique per km [53, 54].

These variations require the skier to master rapid changes in aerobic and anaerobic energy delivery due to the variations in workload and intensity throughout the track. The physiological capacity of successful world-class skiers exhibits VO_{2max} values from 80-90 and 70-80 mL·min^{-1}·kg^{-1} for men and women respectively [1, 2, 6, 7, 39]. While these body-normalized values are well correlated to uphill performance, the absolute VO_{2max} values (6.5 L·min^{-1}and 4.5 L·min^{-1} for successful men and women respectively) are also important for overall performance. Bergh and Forsberg [3] found that heavy skiers were favored in all types of terrain, and the propelling power of increasing endurance-trained muscle mass outweighed the negative effect of carrying these extra kilos in uphills. A well-trained upper body and high technique-specific VO_{2peak} have been particularly highlighted as a factor of similar importance to the general VO_{2max} for enhancing performance in ODS skiing [2, 55, 56]. However, it can be hypothesized that a high DP VO_{2peak} and especially the absolute values are particularly important for LDS who compete in less hilly terrain.

The speed in the uphill sections of a distance race has been estimated by Norman [6, 17] to exceed even the best skiers' maximal aerobic capacity at 20-30 mL·min^{-1}·kg^{-1}. This has been confirmed by various authors [12, 14, 15], who reported that in XC sprint and distance skiing (i.e. 10 and 15 km races) the anaerobic turnover rate interacts with subsequent periods (in the uphills) of work rates of 120-160% of VO_{2peak}, which is possible due to short recovery sequences in the downhills. The maximal O_2 deficit per se is not seen as an important determinant of performance in distance XC, unlike the ability to repeat frequent workloads above VO_{2peak} in the races [14]. However, Björklund et al. [57] demonstrated that elite skiers had a larger rate of lactate disappearance than lower level ODS. The mechanism behind the ability to recover quickly after high ΣO_2 deficit has been sparsely investigated, but athletes with the highest lactate clearance rate performed better than those with a lower clearance rate after active recovery [58, 59]. This information indicated high demands on anaerobic endurance and the ability to produce energy anaerobically to create the necessary work rate in the uphill sections of the course, but also high anaerobic recover capacity to maintain subsequent performance in the following uphills. Generally, distance skiers produce supramaximal power outputs, well above their VO_{2max} during races [6, 11, 12, 14, 15, 17, 60].

Most studies on work economy in XC skiing indicate that the aerobic energy cost differentiates between skiers of different performance levels [21, 61-69]. Recent studies have also improved understanding of the role of mechanical efficiency in XC skiing, highlighting GE as an important determinant of sprint, distance, and long-distance skiing performance [8, 43, 70-72]. Because of the technical complexity of XC skiing, it may be hypothesized that the magnitude of muscle power transferred into external power and speed may differ between skiers of different levels. Performance will therefore be affected by efficiency. However, efficiency depends on terrain and sub-technique, suggesting that skiers optimize their efficiency in the sub-techniques mostly used in a particular format. Accordingly, it can also be hypothesized that long-distance skiers have particularly high efficiency in DP [42, 43].

The demands of long-distance races have been sparsely explored. Most races have long traditions and go from one town to another. This structure distinguishes long-distance events from Olympic distance races in form and especially in course profile (Fig 19). However, some of the courses in the Visma Ski Classics, such as Birkebeineren, have many similarities to Olympic courses and many LDS have previously competed in sprint and/or distance XC skiing. Accordingly, many similar physiological demands as for Olympic ski races are present in long-distance races. However, long-distance races are normally longer and performed in more steady and less hilly terrain [42], with an range in race duration of 1.5 - 4.5h (Fig. 19) . These races are therefore mainly performed in DP, and contain fewer sub-technique transitions and metabolic changes due to the lower number of terrain variations than in the Olympic races. Therefore, a high anaerobic threshold and DP seem critical. Stöggl et al. [25] found that the best skiers have the same pacing strategy as described in marathon runners (negative split), exercise intensity in the races around anaerobic threshold (mean ~82% of HR_{max}) and technically, the best LDS had a long cycle length without compromising cycle rate [25, 44]. However, the few studies so far published on successful long-distance skiers [42, 43] reported lower VO_{2max} (75-80 $mL \cdot min^{-1} \cdot kg^{-1}$ and 5.80-6.10 $L \cdot m^{-1}$ for men), but similar VO_{2peak}/VO_{2max} ratio and better DP efficiency compared to ODS [42, 43]. There are no studies of female long-distance skiers to date.

The ability to decide the finish sprint for the win in both Olympic and long-distance competition is important in modern XC skiing since most competitions are organized as mass starts [20]. Movement-specific strength, especially in the upper body, and the ability to produce power and high V_{max} in DP and G3 skating as well as to accelerate and achieve high speed even at fatigued state are considered important for racing performance [20]. Earlier studies [21, 61] demonstrated that both male and female skiers' work economy was associated with their upper-body maximal strength, while Skattebo et al. (2016) showed that heavy strength training did not improve XC performance in junior females. In XC training much time is devoted to both maximal strength training and general core strength, aiming to prevent injuries and use an efficient technique. However, different approaches to strength training among high-level skiers bring up the questions of how strong one needs to be and in which strength exercises one needs to be strong [52].

Training characteristics of XC skiers and long-distance skiers

The only scientific study to date on training in long-distance XC skiers reported an annual training volume of 775 h, distributed as 83% low-intensity training (LIT), 3% moderate-intensity training (MIT), 6% high-intensity training (HIT), 7% strength training, and 2% speed training [43]. Most of the HIT training is linked to test races and Olympic distance competitions, while long-distance competitions are mostly performed as MIT. This is similar to the distribution reported for world-class ODS, with 750–950 h of annual training volumes distributed as 88–91% LIT, 3–7% MIT, and 4–6% HIT, with an equal focus on classical and skating styles [9, 56, 59, 73]. However, one would expect long-distance skiers to include more DP in their training, to focus more on flat terrain, and to include more sport-specific sessions to meet the demands of long-distance XC skiing. Nevertheless, more detailed data on the training characteristics of long-distance XC skiers are currently lacking.

Modern XC skiing technique

Speed in XC is determined by two essential factors, CR and CL. However, CR and CL vary due to the quadrupedal nature of XC, involving simultaneous engagement of the upper and lower body in independent muscle work. An upper body more specifically trained for DP will positively influence DP speed and efficiency by improving the technical solutions [74] and by delaying fatigue in long-distance DP competitions [75]. In this context, Zoppirolli et al. [45] examined the kinematic changes during the Marcialonga long-distance race and reported that the best LDS could maintain their technique and cycle length better than lower-level skiers.

Skattebo et al. [43] found no kinematic differences between ODS and LDS that could explain the efficiency differences in DP. However, technical solutions in DP in specialized LDS are currently almost unexplored. Accordingly, detailed technical differences and muscle activity should be examined in LDS and compared to the patterns achieved by ODS.

The technical factors associated with DP performance in ODS include a "high hip, high heel" strategy, with a clear forward fall of the body during the poling phase [55, 76]. An effective repositioning led to a high start position followed by rapid downward-forward body movement during propulsion to rapidly generate pole force during a short dynamic poling phase. Furthermore, Holmberg et al. [55] characterized elite skiers as having an almost vertical pole plant during DP in relatively level terrain. A more vertical pole plant is considered important for muscle pre-activation and the stretch-shortening cycle in the shoulder and elbow [55, 77]. Losnegard et al. [33] found sequential muscle activation patterns in DP, where trunk flexor activity preceded hip flexor followed by shoulder and finally elbow extensors. However, it is unknown how this is performed by DP-specialized long-distance skiers or in G3 skating where upper-body work is similar to that in DP. Whether skiers specialized in DP have further developed such kinematical strategies or utilize them differently than less DP-specialized ODS remains to be elucidated. In addition, poling strategies may be influenced by pole length, as shown previously by Losnegard et al. [33].

Upper body performance and physiology

The effectiveness of DP is dependent on production of ground reaction force, which is largely generated by the upper body. The unique movement pattern of the upper body (~50% of total body weight) during DP requires high movement-specific aerobic power [55], in which VO_{2peak} in DP has gradually increased. This necessitates a substantial amount of specific endurance and strength training of the upper body in all XC skiing disciplines. Consequently, the underlying physiological mechanisms are also developed.

The upper body physiology is distinguished from that of the legs by a lower ability to extract and utilize oxygen (O_2). The upper body's lower amounts of type I fibers, but higher of types IIa and IIb, fewer blood capillaries, mitochondria and oxidative enzymes than the legs have been suggested as explanations for these differences [78]. These differences, which are attributed to higher diffusion distance, lower mean transit time of blood in muscles, and lower diffusion area in the upper body compared to the legs, have been shown to affect the extraction and utilization of O_2 in the upper body [78]. Furthermore, the disadvantages of aerobic endurance capacity in the upper body depend not only on intrinsic factors but also on a smaller muscle mass involved. External forces can affect mean capillary tension and reduce blood flow and mean transit time of blood in muscles, thereby creating lower O_2 delivery and vascular recoil to the heart, thus reducing aerobic endurance capacity. However, in elite XC skiers, a VO_{2max}/VO_{2peak} ratio of 95% has been documented [1]. Holmberg pointed out already in 2005 [55] that further improvement in speed and performance in XC skiing depends on increased capacity (technique, strength and endurance) and well-trained upper body and arms. Since then, training of XC skiers' upper body has been emphasized more, and several scientific experiments have tested different training strategies for increased upper-body strength [21, 61, 79-81], endurance [82, 83] and performance [42, 43] without being able to show a VO_2 leg/upper body ratio of 100%. However, based on the research of Boushel et al. [84], Holmberg [1] suggested that improved endurance capacity in the upper body may depend on high volume LIT, e.g. 5-6 hours continuous arm and upper body work at 55-60% of HR_{max} per day for an extended period. After a 42 days of ski trekking with a sledge, using extensive upper body work, over the Greenland glacier a significant increase in blood flow, O_2 delivery and extraction was found. After the expedition, the participants demonstrated a higher armload (Watt), oxygen uptake ($L \cdot min^{-1}$), a-v O_2 difference, blood pressure, increased muscle conductance and peak arm VO_2. Boushel et al. [84] found also a significant translation in muscle fiber composition from less type II to more type I, with increased capillary density and diffusion area in fiber type I. In contrast, total capacity and leg capacity remained unchanged. The findings of Boushel et al. [84] are translated by LDS into practical training routines and implemented in a functional daily training program adapted to their specific DP mode, but this has been sparsely investigated.

Pole length manipulation

The use of longer poles has been shown to increase skiing efficiency and performance in DP and two previous studies showed positive effects of increased pole length on snow in the classical style [32, 37]. However, whether increased pole length could be beneficial in skating, at least in some of the sub-techniques, has not yet been examined in roller skiing or ski skating on snow. In addition, no previous study has addressed the self-chosen pole lengths of male and female skiers and possible relationships to performance. In order to maintain classical skiing as a competitive style and therefore prevent skiers from using the DP technique exclusively, the FIS limited pole lengths to <83% of body height while wearing ski boots in the classical technique (FIS, 2020). In skating, the normal pole recommendations are ∼20 cm below body height although FIS regulations do allow poles up to body height [51]. One may assume that most skiers employ poles close to the limit in classic, while a larger range of pole lengths could be expected in skating.

Today, DP is widely used even in uphill sections of the XC track by both male and female XC skiers [31, 36, 55, 85]. However, the possible benefits of longer poles in steep uphill DP and in the skating technique have not been systematically evaluated, which is particularly interesting in the skating style since the poles are only limited to the skier's body height [51]. It is therefore hypothesized that similar advantages as in DP will occur in skating, particularly in G3 skating where poling movement is restricted by most of the same factors as in DP [86]. G3 is normally used on flat and slightly uphill terrain, and the way potential energy is gained between pole plants, the propulsive force in the poling action, and the conformity in upper-body muscle work are similar to DP. This shows a potential to enhance G3 speed and thereby use this sub-technique effectively in uphill sections with longer poles similar to those in DP. The mechanisms behind enhanced performance of longer poles in DP are reduced O_2 cost [31, 36, 87], resulting from reduced vertical displacement of center of body mass (CoM) and longer poling time. Longer poles in DP give a more upright body position, reduced distance between CoM and the poles, a smaller angle of the poles, which provides a more effective posture [33, 88]. Further, longer poles produce greater propulsive force, allowing the skier to use the upper body and body mass more effectively [86, 88]. As pointed out by Carlsen et al. [31], longer poles and a more upright body position will reduce the total range of motion (RoM) on steep uphill terrain. To what extent these findings also apply to uphill DP and the skating technique has not yet been examined. In addition, a possible advantage of longer poles in DP must be weighed against the possible disadvantage of using the diagonal stride.

Objective and specific aims

The overall objective of this thesis was to examine training characteristics and pole length manipulation for optimizing poling performance and associated physiological and kinematical capacities in long-distance and Olympic distance cross-country skiing.

In order to answer the overall objective, two specific aims were:

1) To compare physiological capacities, and kinematical patterns in double poling between Olympic distance and long-distance XC skiers, and analyze the training characteristics of long-distance XC skiers (Studies I and II)

Approach: Study I compared the physiological and kinematical responses in DP between Olympic distance and long-distance cross-country skiers while treadmill roller skiing, while study II investigated the training characteristics of world-class male long-distance cross-country skiers by using training diary data generated through questionnaires, and follow-up interviews.

2) To describe choice of pole lengths among competitive XC skiers and evaluate the effects of pole length manipulation on performance in the classical and skating style of XC skiing (Studies III-VI).

Approach: Studies III-V examined the effects of increased pole length in DP, G3 skating and on-snow skating on performance, physiological and perceptual responses, as well as sub-technique selection. Study VI described the use of pole and ski length in competitive XC skiers and examined the influence of sex and performance level.

Chapter 2 Methods

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

Subjects

A total of 128 male and 45 female ODS or LDS skiers voluntarily participated in the research constituting this thesis. The characteristics of all skiers are presented in Table 1. Study I and II included world-class LDS.

Table 1: Characteristics of the participants presented as means ± standard deviations (SD) for Studies I-VI

		n		Age (yr)	Body mass (kg)	Body height (cm)	VO_{2max} (ml·min^{-1}·kg^{-1})	FIS points	
		M	F					Sprint	Distance
Study I	LDS	5		28.8 ±5.1	80.2±8.0	183.1±7.4	70.4±2.9	253.7±158	70.66±56
	ODS	7		22.3±1.9	74.2±5.7	182.3±5.4	69.1±4.2	94.2±98	98.0±20.6
Study II		12		30.4±3.7	77.0±6.3	182.7±5.6	80.1±3.6	24.5±18.2	55.3±45.7
Study III		8		22±1.1	77.1±5.0	183±3.6	69.4±5.5	194.1±78.4	120.5±44
Study IV		10		20.1±2.8	73.1±4.6	180.6±3.3	72.4±3.0	236.2±117	147±83
Study V			9	22.9±3.5	1.69±0.1	60.8±4.6	63.6±6.2	184.5±83.9	100.2±33.2
Study VI	M	87		22.8±2.7	75.5±6.3	1.83±0.1	75.6±4.7	93±59	95±123
	F		36	24.1±4.5	59.9±2.4	1.68±0.1	65.8±4.7	157±105	101.5±59.8

LDS=long-distance skiers; ODS=Olympic distance skiers; M=male; F=female; n= number of participants

The participants in Study I were matched and classified as elite/international ODS and world-class LDS [89]. Based on performance level (FIS points or performance in Visma Ski Classics), all participants were defined as national skiers or world class skiers. Studies III-VI included senior national and international Olympic distance skiers. All participants in Study II had two or more top three performances in the highest-ranked long-distance races (Vasaloppet, Birkebeineren, Marcialonga). The participants in Study VI were male and female skiers in the Norwegian championship (Olympic distance format) in 2020 and their FIS points ranged from 0 to 400 before the championship. Studies V and VI included national-level female skiers. All identifiable subjects depicted in illustrations in this thesis have given their written permission for this.

Instruments and materials

Laboratory measurements

The skiers in studies I, III and IV were tested on a treadmill (Rodby 3500ML, Södertalje, Sweden and a 5 x 3 m treadmill Forcelink Technology, Zwolle, The Netherlands) on roller skis in classic and skating style in the testing laboratories in Meråker and Trondheim (Olympiatoppen). All skiers were familiar with treadmill skiing through their training routines and regular physical testing. All skiers used the same pair of roller skis (SWENOR skate or classic with standard resistance wheel 2, Trøsken, Norway) to reduce variations in rolling resistance. Rolling friction force was measured in a towing test as previously described by Sandbakk (2010), providing an average μ value of 0.017, which was used to calculate the work rate.

The skiers used their own poles manipulated for length on different uphill inclinations. The poles were provided with special carbide tips to prevent them from slipping on the treadmill belt. The skiers were always secured with a safety harness hanging from the ceiling, connected to the treadmill's safety brake system. The running VO_{2max} tests were performed on a motor-driven treadmill (Rodby 2500ML, Södertalje, Sweden). The tests were preceded by a standard warm-up, a running or skiing protocol at 60–70% of maximum heart rate for 10 min. The treadmill's inclination and speed were calibrated each time the treadmill was routinely serviced and were checked before each study and no drift in speed or inclination was observed during the test period.

Physiological measures in Studies I, III and IV

An Oxycon Pro apparatus with a mixing chamber (Jaeger GmbH, Höchberg, Germany) was used to measure maximal and submaximal oxygen uptakes. The system has previously been validated by Foss and Hallen [90]. Before each study and test series, the $\dot{V}O_2$ and $\dot{V}CO_2$ gas analysers were calibrated against ambient air and a commercial mixture of high-precision gases (15.00±0.04% O_2 and 5.85±0.1% CO_2, CareFusion gas GmbH, Höchberg, Germany). The flowmeter was calibrated with a 3-L high-precision syringe (Hans Rudolph Inc., Kansas City, Missouri, USA). Heart rate was measured with a heart rate monitor (Polar RC3GPS/V800, Polar Electro OY, Kempele, Finland during the whole test or at the latest 30 sec of the test. Blood lactate in 20 µL of blood was taken from the fingertip and measured using the stationary BIOSEN C-Line lactate analyser (Biosen, EKF Industrial Electronics, Magdeburg, Germany). BIOSEN has previously been validated by Montagut et al. [91]. The subjects' RPE was registered using the Borg (6–20) scale [92].

Kinematics and EMG

Study I

In Study I, the kinematic analysis of DP was conducted according to the procedures in Danielsen et al. [93]. A three-dimensional motion capture system (Qualisys, Gothenburg, Sweden) consisting of eight Oqus 400 cameras captured kinematic data from reflective markers at a frequency of 250 Hz using Qualisys Track Manager. The 3D motion capture system was synchronized with the EMG recordings, using the Musclelab 6000 system (Ergotest Technology AS, Langesund, Norway). Reflective markers were placed on the following anatomical landmarks: styloid process of ulna, lateral epicondyle of humerus, lateral end of acromion process, greater trochanter, lateral epicondyle of femur, lateral malleolus and head of fifth metatarsal (on the ski boot). These markers defined these six body segments: foot, shank, thigh, trunk including head, arm and forearm. Markers were placed 10 cm below the right pole grip and at the bottom of the right pole tip. Raw position data was low pass filtered (4th order Butterworth) at 15 Hz. Segment position data were used to calculate CoM using the segmental inertial properties of de Leva [94], and joint angles (elbow, shoulder, hip, knee, ankle) and pole angle was calculated based on pole markers (Fig. 2). The time between pole on and off defined the poling phase, consecutive pole plants defined one movement cycle, and the time between pole off and on the swing phase. These elements were defined by using the (peak) second derivative of pole tip marker position data.

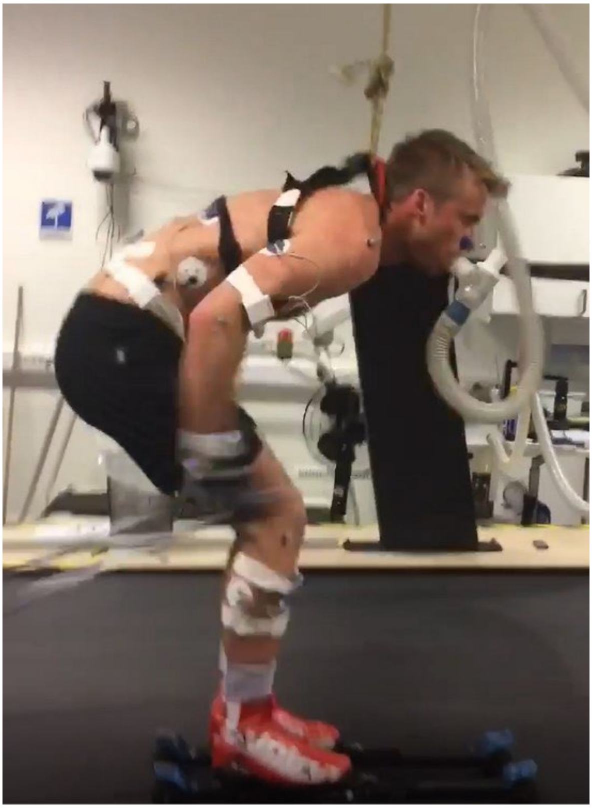


Figure 2: An Olympic distance skier testing gas exchange, kinematics and EMG in the laboratory

EMG was evaluated based on SENIAM recommendations [95], using Musclelab v.10.5.60 (Ergotest AS Porsgrunn, Norway). EMG was evaluated in nine muscles: a) triceps brachii, b) erector spinae at L4-L5, c) rectus abdominis, d) latissimus dorsi, e) gluteus maximus, f) biceps brachii, g) rectus femoris h) gastrocnemius, h) tibialis anterior and i) biceps femoris. The skin was prepared by shaving, abrading, and cleaning with isopropyl alcohol to reduce skin impedance before positioning the electrodes over each muscle. To strengthen the signal, conductive gel was applied to self-adhesive electrodes (Dri-Stick Silver circular sEMG Electrodes AE-131, NeuroDyne Medical, Cambridge, MA, USA). The EMG raw signal was amplified and filtered using a preamplifier as near the pickup point as possible to minimize external noise. The common-mode rejection ratio (CMRR) was 106 dB, and the input impedance between each electrode pair was $>10^{12}$ Ω. The EMG signals were sampled at a rate of 1000 Hz. Signals were band-pass (fourth-order Butterworth) filtered with cut-off frequencies of 20 Hz and 500 Hz, rectified, integrated and converted to root-mean-square (RMS) signals using a hardware circuit network to create the linear envelope of the EMG signal (frequency response 450 kHz, averaging constant 12 ms, total error ±0.5%) [96]. All kinematics and EMG data were time normalized for each participant and cycle and averaged over ~10 cycles for each speed. For each muscle, the occurrence of peak EMG in relation to normalized cycle time at each speed was calculated. Cycle average normalized EMG ($nEMG_{avg}$) at all speeds was computed by normalizing cycle average EMG of each sub-maximal speed to peak EMG measured at each participant's V_{peak} [97, 98].

Upper-body strength and body composition

In Study I, 1RM strength and power were determined in a fixed sitting pull-down exercise simulating the DP movement, emphasizing elbow extension, shoulder extension, and trunk flexion movements [80, 99]. (Fig. 3). Prior to the 1RM strength test, they performed four submaximal loads at 60%, 70%, 80% and 90% of their estimated 1RM with respectively 10, 8, 6, and 3 repetitions. 1RM was determined by increasing the load by 1.25–2.5 kg per attempt until 1RM was achieved. The 1RM results were further converted to mean power by multiplying mass with mean velocity of the pull-down movement, as earlier described [100]. Mean velocity was measured with a linear encoder at 200Hz (Muscle Lab Power, Ergotest Innovation AS, Porsgrunn, Norway), and data was processed with the associated computer software program (MuscleLab 3010E, software version 7.17; Ergotest Technology AS).

All athletes were evaluated for body composition using the InBody 770 device (InBody 770, Cerriots, CA, USA). This included body mass, fat-free mass, and distribution of total body mass in the trunk, legs, and arms. When comparing actual fat-free mass and fat mass, previous studies have shown that the InBody 770 is a valid alternative to dual energy X-ray absorptiometry (DEXA) in trained men and women [101]

Figure 3: Long-distance skier testing 1 RM strength and power in a cable pull-down apparatus.

Study IV

In Study IV, the skiers were filmed in 2D during submaximal treadmill roller skiing using an Apple iPad with 30 frames/sec, and the video recordings were analyzed for cycle length, cycle time and cycle rate in the Coach's Eye software (TechSmith Corp, USA). These cycle properties were calculated using the average of 10 cycles during the last 30 sec of the highest intensity in each condition (pole length, speed and inclination). Cycle time was the time between two pole plants on the left. Cycle length was calculated by multiplying the velocity of the treadmill and the cycle time. Cycle rate was calculated as cycle time divided by one sec. Knee angle was evaluated at the lowest position, where the legs were parallel just before the left leg push.

Field tests

In Study V, two-time trial races on snow were performed in a FIS-standardized track as a simulated 5 km XC skating competition (Fig. 4). Based on distance from the start, the track was divided into five 1-km track sections (S1-S5). Section 1 consisted of varied terrain, while section 2 included two hills with mean inclines of 9.3% and 5.7% and lengths of 259 m (26 m climb) and 272 m (19 m climb), respectively. Section 3 contained varied terrain and included two short hills with 5 and 8 m climbs. Section 4 included the longest uphill of 396 m (41 m climb). Section 5 included an uphill of 272 m (19 m climb where the steepest part was 18.6%). The two main downhill parts of the track contained mean downhill slopes of 7.8% and 5.8% and lengths of 407 m and 182 m in sections 2 and 4, respectively. The maximal difference in elevation was 41.5 m, with a total climb of 176 m for the entire track.

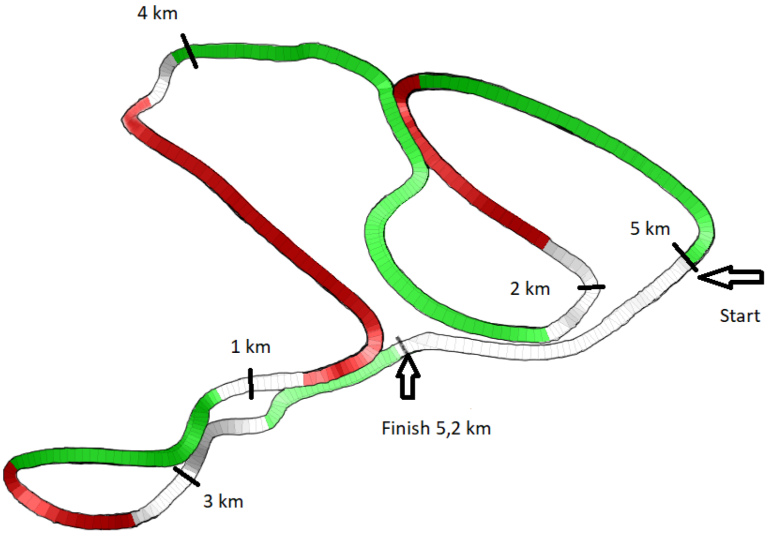


Figure 4: Track profile of the entire 5.2 km track used in the simulated competition. Red shows uphills, green shows downhills and gray-white shows flat sections.

Immediately after the competition, blood lactate concentration (Lactate Pro LT-1710*t* kit, Arkray Inc., Kyoto, Japan), RPE [92] and throughout the whole race mean heart rate (Garmin Forerunner 935 GPS, Garmin Ltd., Olathe, KS) were evaluated. Course and elevation profiles were determined with a Catapult Optimeye S5 (Cat-S5) (Catapult Sports, Melbourne, Australia). The Cat-S5 has recently been validated [15, 102] with a reported section-time error of between 0.1 and 0.2 sec for 20- to 180-m long sections [47, 102]. The subjects were timed with the Racesplitter application.

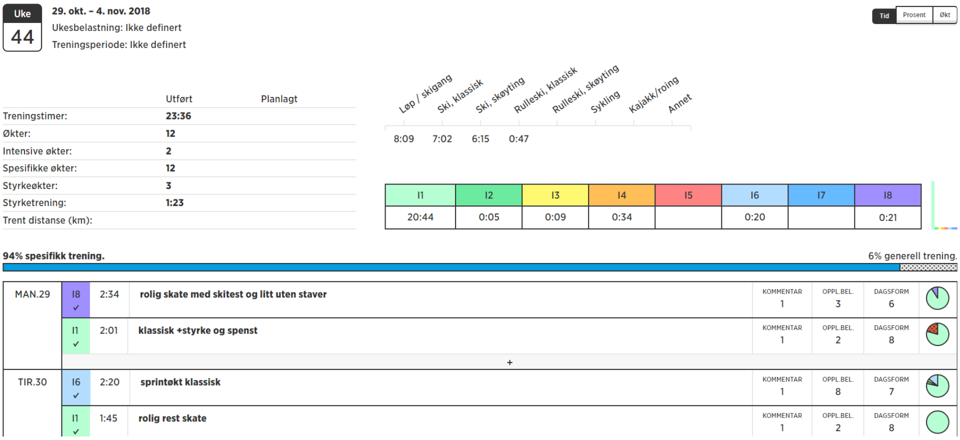
Evaluation of sub-techniques G2-G4

In Study V, to identify where participants used the G2, G3, G4 skating sub-techniques on the track, a questionnaire was prepared and used in combination with the course map in a subsequent interview with each participant. Directly after the simulated races, the participants also provided subjective RPEs [92] and their perception of their skiing technique on a scale from 1-10 with ordinary and long poles.

Questionnaires

In Study II, an online questionnaire was developed (https://nettskjema.no/) to analyze the world-class LDS training routines. It contained 93 questions: 61 questions asking for a numerical value, one yes/no question, three multiple-choice questions, and 26 open-ended questions. Participants reported their demographic information, performance, and training characteristics during their most successful Visma ski classic tour (VSC) year. The questionnaire also contained questions about details of how they designed typical training sessions to meet the demands of the VSC.

In Study VI, data were collected via an online questionnaire (https://nettskjema.no/) in which the athletes self-reported their anthropometric, physiological, and training characteristics, previous FIS points in distance and sprint, in addition to ski and pole length in classic and skating styles. The questionnaire was designed to take 7–10 minutes to complete and contained 13 questions: 12 questions asking for a numerical value and one open-ended question. The online questionnaire was distributed to 156 male and 71 female participants through Facebook Messenger, based on the result list from the National Championships 2020 for 10 and 15 km individual time trials for women and men. Participants were asked to report their pole and ski lengths for the classical and skating techniques. Fifty-four percent of the athletes in the championships (57% of males, 51% of females) (range 0-400 FIS points) provided information about their skiing equipment.



Uke
44

29. okt. – 4. nov. 2018
Ukesbelastning: Ikke definert
Treningsperiode: Ikke definert

	Utført	Planlagt
Treningstimer:	**23:36**	
Økter:	**12**	
Intensive økter:	**2**	
Spesifikke økter:	**12**	
Styrkeøkter:	**3**	
Styrketrening:	**1:23**	
Trent distanse (km):		

Løp / skigang	Ski, klassisk	Ski, skøyting	Rulleski, klassisk	Rulleski, skøyting	Sykling	Kajakk/roing	Annet
8:09	7:02	6:15	0:47				

I1	I2	I3	I4	I5	I6	I7	I8
20:44	0:05	0:09	0:34		0:20		0:21

94% spesifikk trening. 6% generell trening.

MAN.29	I8 ✓	2:34	**rolig skate med skitest og litt uten staver**	KOMMENTAR 1	OPPL.BEL. 3	DAGSFORM 6
	I1 ✓	2:01	**klassisk +styrke og spenst**	KOMMENTAR 1	OPPL.BEL. 2	DAGSFORM 8
	+					
TIR.30	I6 ✓	2:20	**sprintøkt klassisk**	KOMMENTAR 1	OPPL.BEL. 8	DAGSFORM 7
	I1 ✓	1:45	**rolig rest skate**	KOMMENTAR 1	OPPL.BEL. 2	DAGSFORM 8

Figure 8: Example of online training diary (Olympiatoppen) recorded by an Olympic distance skier, from week 44 in the preparation period. It contains day-to-day training data, weekly hours, training sessions, training content, intensity distribution, training mode, perceived exhaustion, daily fitness, and comments.

Technique definitions and kinematics

In studies I and III, classic skiing sub-techniques were DP from flat to level terrain and diagonal stride in uphills. DP is a sub-technique where the upper body and arms generate all propulsion, although the legs and hip are of crucial importance to the repositioning between each poling, through the poles [103]. The modern movement pattern is characterized by its double pole plant and extended use of the upper body, flexion of the trunk and hip joint, followed by the flexion-extension pattern of the shoulder and elbow joints [55]. Diagonal stride is mainly used in uphill sections of XC tracks and involves a diagonal movement pattern of the arms and legs. Before the kick, the skier must press the ski into the snow and produce enough friction via the kick wax for the ski to grip the snow and be stationary during the kick [104].

In Studies IV and V, different skating sub-techniques were used, mainly G2, G3, and G4. G2 is primarily used in steeper inclines and involves an asymmetric DP pattern on every second leg kick. The challenge is to synchronize and coordinate the four asymmetric and different force impulses from the right and left arms and legs into forward propulsion when this technique is used in uphill sections of the track. The G3 technique uses the abdominal, upper body and arm muscles in an asymmetric pole plant with a one leg push-off for each plant. G3 is mainly used in flat terrain but has lately evolved into an effective uphill technique in modern XC. G4 involves the symmetric use of the upper body and arms in the poling phase coordinated with every second leg push in downhills and flat terrain. Its effectiveness depends on coordinating the forward swing of the arm with the leg push on the non-poling side.

Test protocols

Warm-up for laboratory testing and preparation for the field test was standardized at 10-15 min at 60-75% of HR_{max} in running or skiing in the sub-techniques (G2, G3, G3 and DP, diagonal stride) used during testing. In studies I, III, IV and V, the participants prepared for all tests as for a regular competition [16]. Each participant arrived at the test lab or ski venue one hour before for a short interview to ensure that they were well nourished, hydrated, motivated and healthy. The participants in studies I, III, IV and V had from five to 48 hours between each time trial and were instructed to rest in the final two hours before warm-up for test two.

Double Poling

In Study I, oxygen uptake, kinematics, EMG, heart rate, blood lactate, TTE and RPE were evaluated in a DP ramp protocol (Fig. 5). The participants skied on the treadmill at a fixed inclination of 5% uphill on classic roller skis, starting at 10 km·h^{-1} with a speed increase of 1.5 km·h^{-1} per minute until exhaustion.

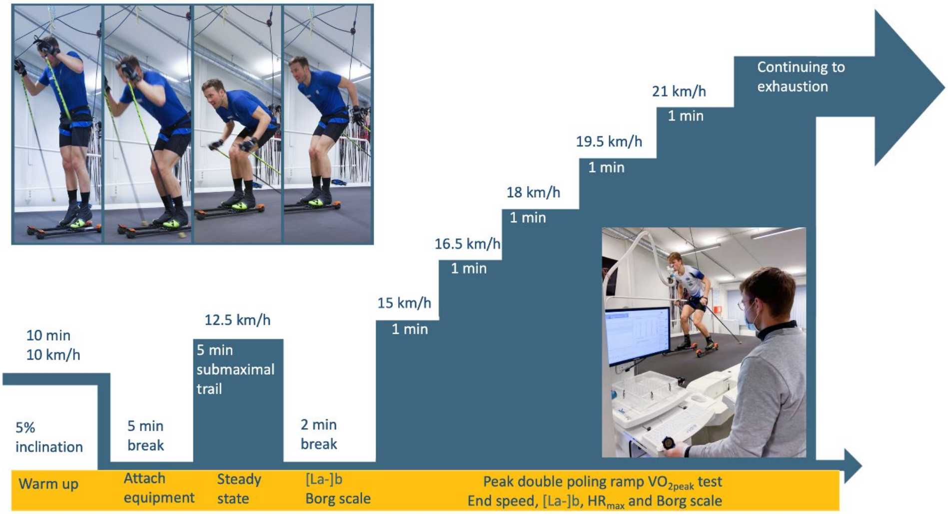


Figure 5: Schematic submaximal steady state and ramp VO_{2max} test protocol in double poling (Study I), increasing by 1.5 km·h^{-1} every min until exhaustion.
Double poling VO_{2peak}, peak oxygen uptake in double poling; [La-]b, blood lactate; HR_{max}, maximal heart rate.

In study III, VO_{2peak}, oxygen cost, HR, blood lactate, time to exhaustion and RPE were determined in DP. The subjects skied on the treadmill at a fixed speed (10 km·h^{-1}), starting out at 7% inclination, and the inclination was increased by one degree every minute until exhaustion (Fig. 6).

Diagonal Stride

In study III, VO_{2peak} and performance were measured during diagonal stride on a skiing treadmill (Fig. 6). The speed was fixed at 10 km·h^{-1}, and the participants started at an inclination of 7%, increasing every minute until exhaustion. Exhaustion occurred at 15-18% inclination.

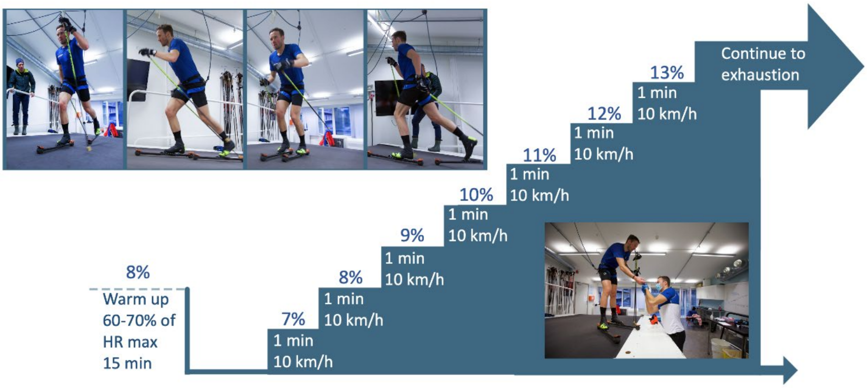


Figure 6: Schematic ramp protocol, Study III, VO_{2max} and heart rate were continuously measured in diagonal stride, and RPE and blood lactate were obtained immediately after exhaustion.

Skating technique

In studies IV and V, the participants used the G2, G3 and G4 skating techniques. In study IV, the participants performed uphill G3 skating on the treadmill using self-selected and long poles. Peak oxygen uptake was measured in a standard protocol, where speed was increased every minute (2 km·h^{-1}) from 14 km·h^{-1} at 4% inclination until exhaustion. To investigate the effect of pole length in G3, two protocols were used. The first used treadmill inclines of 7%, 9% and 11% at a constant speed of 10 km·h^{-1}.

The second protocol used speeds of 14, 17 and 20 km·h^{-1}, with a constant incline of 4%. Each step contained 2 x 5 min with self-selected poles and self-selected +7.5 cm. There was a 1-min recovery between each 5-min step to measure blood lactate concentration, record perceptual response and change poles (Fig. 7). During each test, VO_2 uptake and heart rate were measured continuously. GE was calculated based on VO_2 data and RER values from the two last min of each 5-min interval [70]. Kinematical variables, cycle time, cycle rate, cycle length and knee angle were measured in skating at the last step of each test (11% and 20 km·h^{-1}).

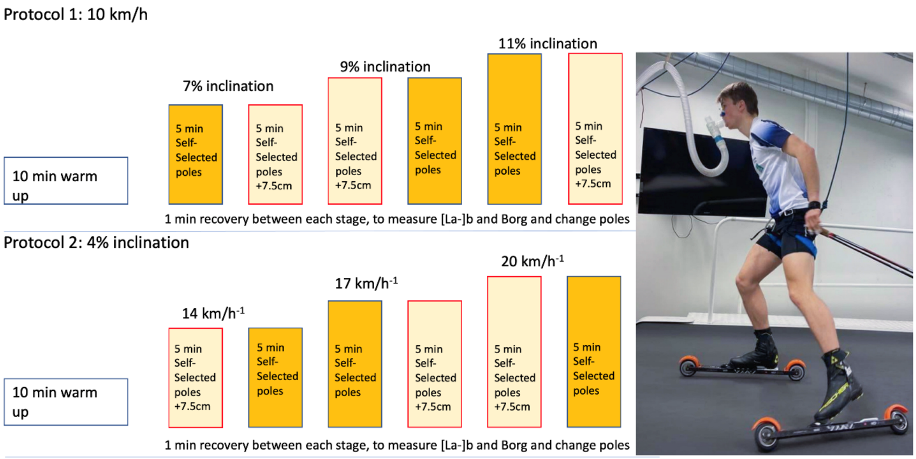


Figure 7: Schematic protocol, Study IV, in a steady state ramp protocol, comparing self-selected poles and self-selected +7.5 cm poles in G3 skating on a roller ski treadmill. VO_{2peak} and heart rate were continuously measured, and Borg scale and blood lactate were obtained immediately after each stage.

In study V, the participants self-identified their use of G2, G3, and G4 skating sub-techniques in the different zones of the track with self-selected poles and self-selected +7.5 cm poles in a crossover design. In the two simulated races, participants were timed and analyzed for heart rate, end lactate, RPE, and perceived feeling of how the long poles were to ski with compared to self-selected poles.

LDS Training analyses

In study II, training routines were collected via a constructed online questioner based on previous training analyses of world-class XC skiers [73] and fitted to the purpose of the investigation by an expert panel of former athletes, coaches, a physiologist, and researchers with experience from similar projects. Information from the athletes' training diary, written sources or other sources such as online recording of training, e.g., direct storage of training data from a heart rate monitor (Fig. 8) were included in the study. Three participants were interviewed based on the questionnaire to obtain more qualitative information and depth in the data. All training data were organized into phases due to the LDS organization of their season: general preparation period (GP: May-August), specific preparation period (SP: September-November), and competition period (CP: December-April)], training form (endurance, strength, and speed), intensity (LIT, MIT, and HIT), and exercise mode were quantified. LIT was defined as 60-82%, MIT 82-87%, and HIT as >87% of HR_{max} [73].

Statistics

All data in the studies are presented as means and standard deviations (SD), and are checked for normality using the Shapiro-Wilk test and visual inspection of data. The level of statistical significance was set to $p < 0.05$ in all studies. In Studies I-V, effect size was calculated with η^2 (partial eta squared), where $0.01<\eta^2<0.06$ constituted a small effect, $0.06<\eta^2<0.14$ a medium effect, and $\eta^2>0.14$ a large effect [105], interpretation of magnitude was: 0-0.2 = trivial, 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, and >2 = very large [106] and effect sizes for local differences were calculated as Hedges' g_s [107]. Data were processed and analyzed using IBM SPSS Statistics version 24 for Windows (SPSS Inc., Chicago, IL, USA) and Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA). A brief description of statistical methods is presented below, while further specification of statistical analyses is specified in studies I, III, IV and V.

In study I, statistical analysis was performed using a linear mixed model (LMM), with participant specified as a random factor (random intercept model). Due to different speed at exhaustion, the analysis of kinematics and EMG was restricted to speeds between 12.5 and 21.0 $km \cdot h^{-1}$. To compare $_{n}EMG_{avg}$ and timing of peak EMG between groups, with group (LDS, ODS) and speed (12.5-21.0 $km \cdot h^{-1}$) as fixed factors, the timing of peak EMG between the nine muscles, with group and muscle, with group and mode (DP versus running), was used to compare peak physiological variables. To compare variables at submaximal workloads (12.5 $km \cdot h^{-1}$ for DP and 10.0 $km \cdot h^{-1}$ for running), an independent sample t-test was used. An LMM was used to compare the effects of group and speed (12.5-21.0 $km \cdot h^{-1}$) as well as their interaction effects on kinematics. Between-group comparisons of variables at submaximal and peak workloads, as well as possible differences in strength, power, and body composition, were compared using independent t-tests. Despite small number of participants, variables were approximately normally distributed in each group (assessed by normal QQ-plots and the Shapiro-Wilk test), and all Levene's tests for equality of variances between groups showed $p>0.1$.

Study II presented responses from a questionnaire where data were summarized in numerical values to facilitate statistical analysis. Categorical variables were presented as absolute numbers and percentages. To categorize free-text questions, two researchers performed independent content, frequency, and consistency analyses until consensus was reached. Direct verbatim quotations were used to inform interpretation. Descriptive data for continuous variables were recorded as means (*SD*) and for categorical variables as totals and percentages.

In Studies III-V, a one-way multivariate ANOVA with repeated measures on each variable was performed on different conditions (pole length, inclination, velocity, sub-technique and race time), for kinematic, physiological and perceptual variables. Post-hoc comparisons with Holm-Bonferroni corrections were conducted to determine differences. When sphericity assumptions were violated, Greenhouse-Geisser adjustments of the *p*-values were reported.

Paired samples *t*-tests were applied when there were only two means to be compared, i.e., comparisons between the two protocols at each intensity. To compare RPE between the two time-trials, a Wilcoxon ranked sign test was used. In these studies, the results were also presented as means ± SD, except the perceptual responses, which were presented as medians (IQR).

Study VI presented responses from a questionnaire where the data were summarized in numerical values to facilitate statistical analysis. To compare body-height-normalized pole and ski length between men and women, an independent samples t-test was used, while Pearson's correlations were used to quantify the association between performance (FIS points) and body-height-normalized pole and ski lengths. These correlations were categorized as: trivial (<0.1); small (0.1–0.3); moderate (0.3–0.5); high (0.5–0.7); very high (0.7–0.9); or perfect (0.9) [108].

Chapter 3 Results

Study I:

Specific aims and procedures

Study I compared the kinematical and physiological responses to DP between LDS and ODS. Two submaximal workloads and an incremental test to exhaustion were performed to determine GE, VO_{2peak} (DP-VO_{2peak}) and time to exhaustion in DP, an incremental VO_{2max} running test (RUN-VO_{2max}) (Table 2), maximal pulldown strength and body composition (Table 3). Performance and related physiological measurements were determined during all tests, while 3D kinematics (Figs. 9-10) and EMG of selected muscles (Figs. 11-13) were measured during the DP test.

Main results

Compared to ODS, LDS displayed a higher DP peak oxygen uptake (DP-VO_{2peak}) (68.3±2.1 versus 65.1±2.7 $ml\cdot kg^{-1}\cdot min^{-1}$, p=0.050), also relative to maximal oxygen uptake (97% vs 94%, respectively, p=0.075, ES=1.08), higher GE (17.2% versus 15.9%, p=0.029), and higher peak speed (+1.4±0.2 $km\cdot h^{-1}$, p=0.030) (Table 2). There were no group differences in cycle length or cycle rate in DP, although LDS displayed longer relative poling times (~2.4 percentage points) at most speeds compared to ODS (p=0.015). Also found were group versus speed interaction effects ($p<0.05$) for pole angle and vertical fluctuation of CoM, with LDS maintaining a more upright body position and more vertical pole angles at touchdown and lift-off at faster speeds (Figs. 9-10). ODS displayed consistently slightly higher normalized EMG amplitudes than LDS in the rectus abdominis (p=0.074) and biceps femoris muscles (p=0.027) (Figs. 11-12). LDS performed slightly better on 1RM upper-body strength (122 versus 114 kg, p=0.198), with no group differences in power in the pull-down exercise (Table 3).

Table 2: Performance and physiological responses to submaximal and incremental double poling (at 5% incline) and running (at 10.5% incline) in five world-class long-distance skiers (LDS) and seven elite male Olympic distance skiers (ODS). Presented as mean±SD. p-values and g_s are reported for group comparisons (independent t-tests).

Variables	**Double poling**			**Running**		
Performance test	**LDS**	**ODS**	**p, g_s**	**LDS**	**ODS**	**p, g_s**
V_{peak} (km·h^{-1})	22.1 ± 1.0	20.7 ± 0.9		15.1 ± 1.0	14.6 ± 0.8	0.475, 0.42
Peak work rate (W)	336 ± 39	289 ± 33	0.060, 1.22	350 ± 39	320 ± 21	0.176, 0.93
$VO_{2max/peak}$ (mL·min^{-1}·kg^{-1})	68.3 ± 2.1	65.1 ± 2.7	0.043, 1.20	70.5 ± 2.8	69.1 ± 4.2	0.524, 0.33
$VO_{2max/peak}$ (L·min^{-1})	5.5 ± 0.6	4.8 ± 0.3	0.083, 1.31	5.6 ± 0.5	5.1 ± 0.3	0.094, 1.19
RER (-)	1.10 ± 0.03	1.12 ± 0.06	0.467, 0.37	1.17 ± 0.02	1.15 ± 0.05	0.366, 0.45
$HR_{max/peak}$ (bpm)	187 ± 4	184 ± 10	0.466, 0.36	191 ± 4	194 ± 8	0.390, 0.44
Borg (6-20)	18.2 ± 1.3	19.0 ± 1.2	0.304, 0.61	19.6 ± 0.5	19.3 ± 0.5	0.335, 0.57
Submaximal test						
Speed (km·h^{-1})	12.5	12.5		10	10	
VO_2 (mL·min^{-1}·kg^{-1})	39.4 ± 1.2	42.2 ± 2.6	0.033, 1.21	52.8 ± 0.8	54.6 ± 2.2	0.090, 0.91
VO_2 (L·min^{-1})	3.15 ± 0.32	3.14 ± 0.30	0.960, 0.03	4.22 ± 0.42	4.06 ± 0.39	0.530, 0.39
RER (-)	0.88 ± 0.04	0.94 ± 0.04	0.029, 1.45	0.94 ± 0.02	0.94 ± 0.04	0.875, 0.08
Metabolic rate (W)	1074 ± 102	1087 ± 110	0.829, 0.12	1466 ± 170	1408 ± 106	0.524, 0.40
Work rate (W)	185 ± 19	172 ± 13	0.247, 0.74	217 ± 23	202 ± 15	0.247, 0.74
Gross efficiency (%)	17.2 ± 0.5	15.9 ± 1.1	0.019, 1.38	14.8 ± 0.2	14.3 ± 0.5	0.069, 1.00

VO_{2max}, maximal oxygen uptake; VO_{2peak}, peak oxygen uptake; RER, respiratory exchange ratio; HR_{max}, maximal heart rate; HR_{peak}, peak heart rate; VO_2, oxygen uptake.

Table 3 shows body-composition measures and upper-body strength and power for both LDS and ODS. The LDS were heavier than ODS and had rather more muscle mass in the upper body and arms but a lower percentage of muscle mass in the legs. The LDS tend to display higher 1RM in the pull-down exercise than ODS, with no difference in mean power found between the two groups.

Table 3: Body composition and 1RM upper-body strength and power for all participants pooled, five world-class long-distance skiers (LDS) and seven elite male all-round skiers (ODS). Presented as mean±SD.

Variables	Pooled (n=12)	ODS (n=7)	LDS (n=5)	p, g_s
Body composition				
Total mass (kg)	76.7±4.5	74.2±5.3	80.2±7.1	0.190, 0.83
Muscle mass (kg)	40.2±3.7	39.1±2.7	41.8±4.3	0.259, 0.72
Body mass index	23.1±1.5	22.5±1.7	23.8±0.6	0.115, 0.83
Upper body (kg)	30.6 ±2.7	29.6±1.8	32.0±3.2	0.219, 0.83
Percentage of total mass (%)	39.9±1.7	40.0±2.0	39.9±0.9	0.919, 0.05
Arms (kg)	8.1±0.9	7.8 ±0.6	8.6 ±1.1	0.186, 0.89
Percentage of total mass (%)	10.6±0.6	10.5±0.7	10.7±0.5	0.469, 0.39
Legs (kg)	21.4±1.9	21.1±1.4	21.7±2.4	0.664, 0.27
Percentage of total mass (%)	27.9±1.2	28.5±1.0	27.1±0.9	0.037, 1.31
Upper-body strength				
1RM (kg)	117.7±9.4	113.9±12.2	121.5±6.5	0.198, 0.68
1RM/total mass (kg)	1.5±0.1	1.5±0.2	1.5±0.1	0.851, 0.10
Power (W)	748.4 ±101.0	733.1 ±134.3	763.6 ±67.6	0.618, 0.25
Power/total mass (W/kg)	9.7±1.3	9.5±1.8	9.9±0.8	0.776, 0.16

1RM, one repetition maximum.

There were no between-group differences in cycle length or cycle rate at any speed (Fig 9), with no differences in peak values for rate (1.12±0.18 Hz versus 1.04±0.08 Hz, p=0.385, g_s=0.58) or length (6.0±0.7 m versus 5.7±0.6 m, p=0.503, g_s=0.39). The LDS had slightly longer poling times (p=0.193) than ODS, while relative poling times differed (p=0.015) at speeds between 12.5 and 18.0 km·h^{-1} (40-34% versus 37-31% in LDS and ODS, respectively).

Significant interaction effects were found for pole angle at touch down and lift-off, and the LDS were able to maintain their technique with rising speed and exhaustion. There was an interaction effect on pole angle touch down ($F_{5,46}$=10; p<0.001, and $F_{5,46}$=10; p<0.001), pole tip versus toe at touch down ($F_{5,46}$=10; p<0.001) and lowering of CoM ($F_{5,46}$=10; p<0.001). This shows that LDS have a more vertical pole plant, plant the pole tip farther in front of the toe and lower CoM less than ODS (Fig. 9).

Although joint angles appeared to be very similar in both groups (Fig 10), interaction effects were found for knee and hip angles at pole touchdown and for minimum hip angle during the poling phase, with the LDS maintaining a slightly more extended hip positioning at faster speeds (Fig. 10). These differences led to the significant interaction and minor group effects on the minimum center of mass height.

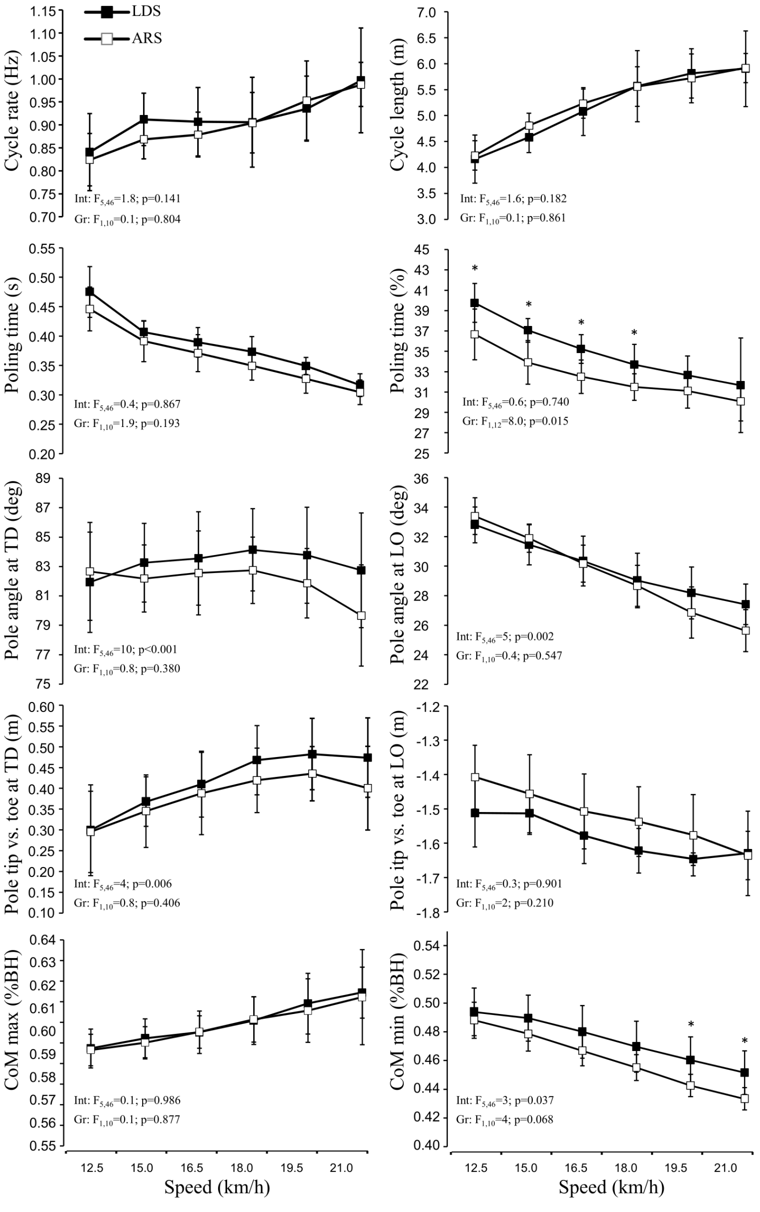


Figure 9: Kinematic responses as a function of speed in long-distance (N=5) versus Olympic distance (n=7) cross-country skiers performing treadmill double poling at 5% inclination. * Significant difference between groups P=0.05.

Int, Interaction; Gr, Group; TD, Pole touch down; LO, Pole lift of; %BH, percentage of body height; m, meter; s, second; CoM max, highest position to center of mass; COM min, lowest position to center of body mass; deg, degree.

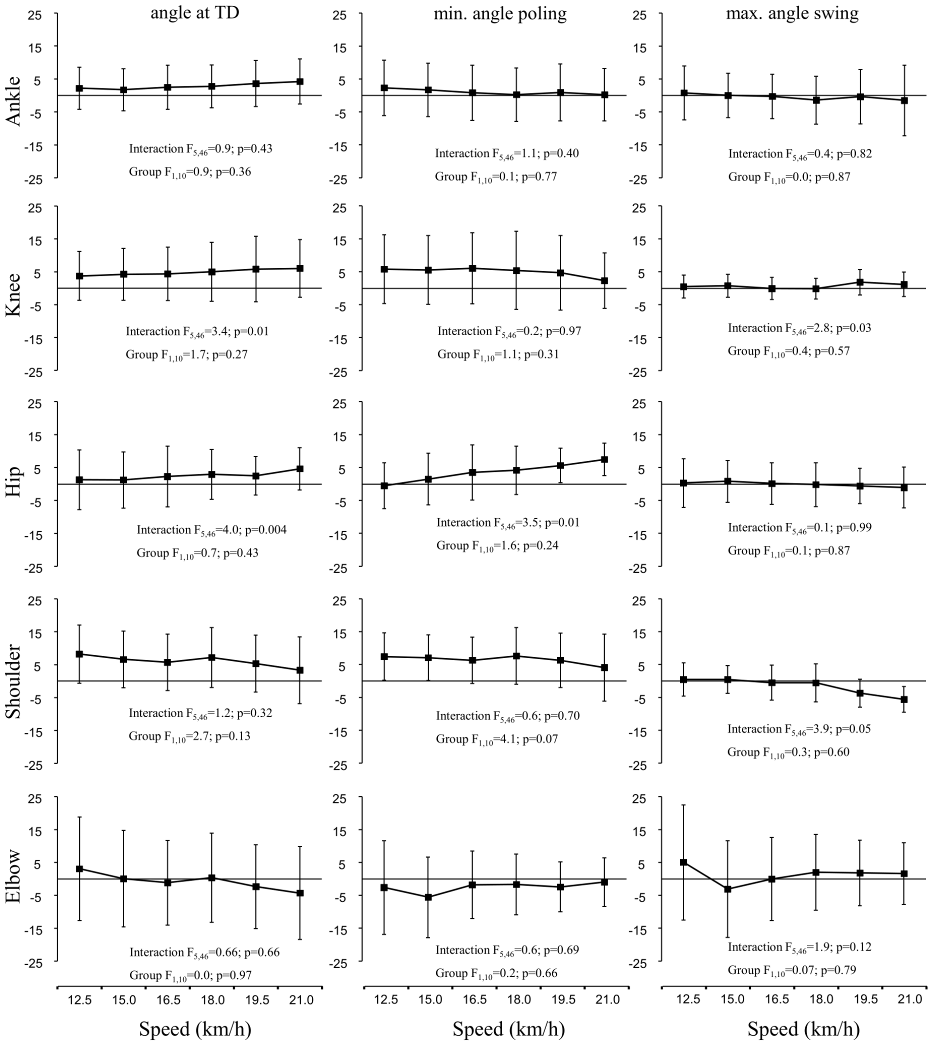


Figure 10: The mean group difference (LDS group minus ODS group) and 95% CI of joint angles at touch down (left panels), the minimum angle reached within the poling phase (maximum angle for the shoulder) (middle panels), and maximum angles reached within the swing phase (right panels), 5% treadmill double poling.

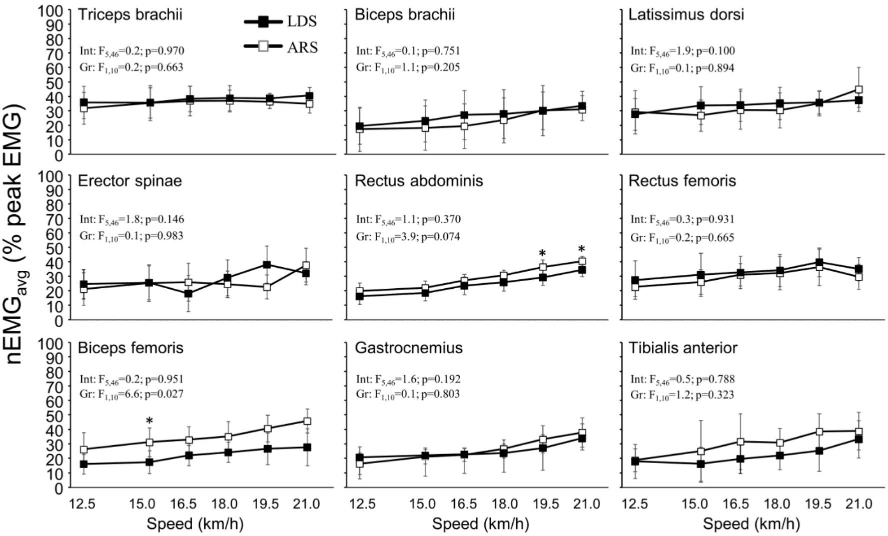


Figure 11: Peak and mean EMG amplitudes (% of maximal amplitudes) for the triceps brachii, biceps brachii, rectus abdominis, latissimus dorsi, biceps femoris, rectus femoris, gastrocnemius, tibialis anterior and erector spinae during DP at 12.5-21 km/h for Olympic (n=7) and long-distance (n=5) skiers at 5% inclination. * Significant difference between groups P=0.05.

DP speed affected nEMG$_{avg}$ of most muscles ($p<0.001$, Fig. 11) but less so for triceps brachii ($p=0.202$), erector spinae ($p=0.177$) and rectus femoris ($p=0.620$). nEMG$_{avg}$ showed a particular increase at speeds above 18 km·h^{-1}Peak EMG amplitudes occurred slightly earlier at faster speeds for triceps brachii, latissimus dorsi, and rectus abdominis ($p<0.01$; $d>1.4$), with basically no systematic difference between groups (Fig. 12). However, nEMG$_{avg}$ in rectus abdominus ($p=0{,}160$) and biceps femoris ($p=0.052$) were somewhat higher in ODS than in LDS (Fig.12). When analyzing the timing of peak EMG amplitudes for all muscles across all speeds, a significant effect of muscle was found ($p<0.001$; $d=2.3$), without any group ($p=0.520$; $d=0.42$) or interaction effects ($p=0.84$; $d=0.44$) (Fig. 13).

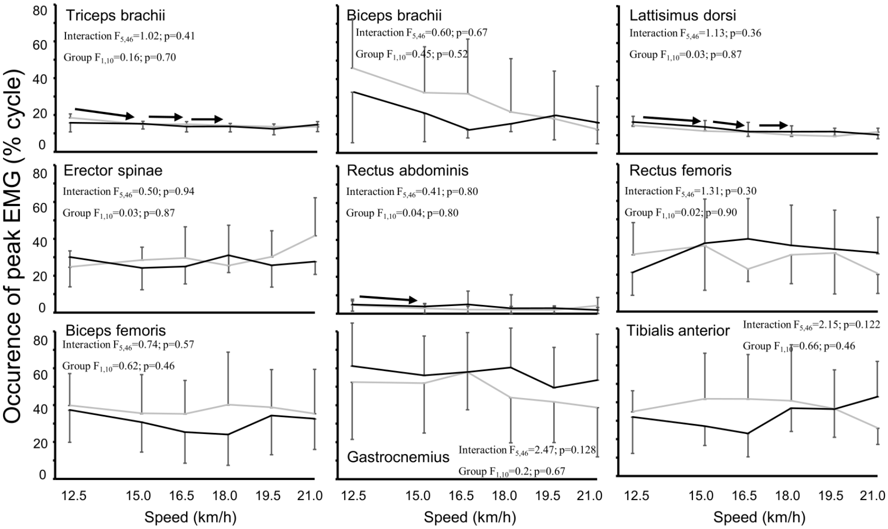


Figure 12: Average normalized EMG ($nEMG_{avg}$) in long-distance (LDS, n=5) versus all-round (ARS, n=7) cross-country skiers performing treadmill double poling at 5% inclination. Int, interaction; Gr, group. * indicates p<0.05.

→ indicates a significant increase in EMG amplitude between these velocities and all right of the sign (p<0.05)

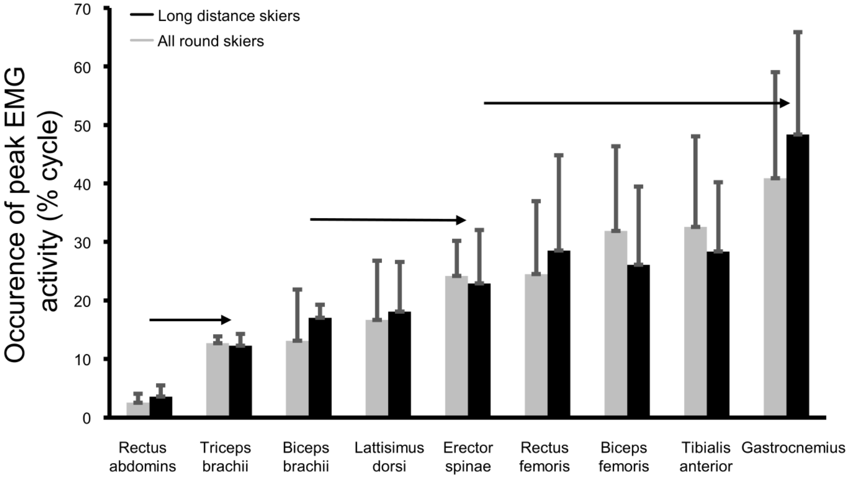


Figure 13:

Occurrence of peak EMG amplitude during the cycle (average across all speeds) for all round (ARS, n=7) and long distance (LDS, n=5) cross-country skiers performing treadmill double poling at 5% inclination. RA, Rectus abdominis; TRI, Triceps brachii; BB, Biceps brachii; LD, Latissimus dorsi; ESP, Erector spinae; RF, Rectus abdominis; BF, Biceps femoris; TA, Tibialis anterior; GAS, Gastrocnemius

→ indicates a significant different to the muscles to the right of the sign (p<0.05)

Timing of muscle amplitudes showed a sequential movement pattern in the muscles engaged in XC skiing and significant differences between LDS and ODS evaluated in a short lab submaximal test in DP (Fig. 13).

Study II:

Specific aims and procedures

This study investigated the training characteristics of world-class long-distance XC skiers, including detailed information about the distribution of training volume, intensity, and exercise modes, as well as specific session designs employed during the skiers' most successful season. Data for this study were collected via an online questionnaire (Nettskjema, 2020) based on previously detailed training analyses of world-class XC skiers (Solli et al., 2017) and adjusted to the study aim by an expert panel of former athletes, coaches, a physiologist, and researchers with experience from similar projects.

Main results

The average annual training volume was 861 ± 90 h, including 795 h (92%) of endurance training, 53 h (6%) of strength training, and 13 h (2%) of speed training. Here, a pyramidal endurance training distribution was employed (i.e. 88.7% LIT, 6.4% MIT, and 4.8% HIT), with 50-60% of the endurance and speed training performed using a specific exercise mode, DP. This training included many long-distance sessions, typically performed as daily 3-5 h sessions. The week-to-week periodization of endurance training load was relatively evenly distributed in GP and SP, while all the skiers maintained a high training volume during training weeks in CP but halved their volume and reduced the amount of DP during weeks with competitions. Tables 4-6 provide insight into the LDS skiers' training methods, exercise mode and content in three examples of training weeks across the annual training season. Tables 4-6 have supplementary data from the interview and verbatim quotes of the athletes and data which are not presented in study II.

Table 4: Specific training sessions for long-distance XC skiing

	Training method	Exercise modes	Description
Continuous training	Long distance specific	DP	• 4 h DP at LIT on flat and undulating terrain, with inclusion of sprints (10 x 10-12 s) in the last hour of the session • 5 h DP at LIT, mainly on flat terrain but steep uphill DP during the last 30 min
	Long distance unspecific	All	• 3 h of steady-state running or skating skiing sessions performed on undulating terrain
	Long distance mix of exercise modes	All	• 4 h LIT steady-state sessions while changing the exercise mode in mid- of the session. For instance, 2 h DP + 2 h running • 5 h LIT steady-state sessions while changing the exercise mode in mid- and end– of the session. For instance, 2 h skating, 1 h running and 2 h double poling
	Progressive long distance	DP	• Progressive session starting with 1.5-2.5 LIT followed by 0.5-1.15 h MIT and 0.5 h HIT. • Progressive 2-4 h session interspersed with sprints and maximal effort during one uphill at the end of the session
	Competitions/test or simulated competitions	DP Running	• Competitions or test races ranging from 30 min to 2 h, often simulating the terrain of one of the main races during CP • General running uphill running test 30-60 min
Mixed training sessions	LIT + intervals	DP	• 3-5 h at LIT followed by an interval session at MIT and/or HIT. Typical sessions are 5-6 x 5-6 min, 15 x 3 min, 30 x 1 min, 5 x 2 min or 45/15 s in 30 min. • 1-2 h at LIT followed by 1 h of MIT
	Interval + LIT	DP	• MIT or HIT interval (examples above) followed by 2-3 h LIT to simulate the fast start in races
	Strength + LIT	DP	• 2-4 h at LIT before or after a strength session (heavy + endurance) described below. • 2 h at LIT, 1 h strength training followed by 1-2 h at LIT
Interval training sessions	MIT intervals	DP DIA Running	• 0.5-1 h warm-up followed by intervals at MIT. Typical sessions: 4-6 x 8–15 min, 10 x 5-6 min or 15 x 3 min with 1-2 min recovery between intervals.
	HIT intervals	DP Running DIA Running with poles	• 0.5-1 h warm-up followed by intervals at HIT. Typical sessions: 4-6 x 4-6 min uphill, 5 x 10 min undulating terrain, or 10 x 2-3 min with 2-3 min recovery between intervals. Short intervals such as 3-5 x 8-10 min (40/20 s, 45/15 s or 30/15 s work/rest with 2 min rest between intervals).
	Competition preparations	DP	• 0.5-1 h warm-up followed by intervals at HIT, often in easy terrain to achieve high speed. Typical session: 4 x 6 min, 5-4-3-2-1 min or 3 x (3-2-1 min) with 1-3 min rest between intervals. • 10-15 min warm-up, 5 x 5 min HIT running on treadmill to rest upper body and trigger or maintain a high maximal aerobic power

	Lactate production training	DP	• 0.5-1 h warm-up followed by intervals at maximal effort. Typical sessions: 10- 20 x 1 min with 1-3 min rest between intervals or 3 x (6 x 1 min) with 2 min rest between intervals and 5 min rest between series.
Strength & speed	Heavy strength		• In the GP; 3-5 repetitions using 6-8 sets using exercises such as deadlift, squat, clean, pull down, chins, toes to bar, back extension, pull over, dips, bench press (narrow grip). • In the SP; 5 x 5 repetition of 5-7 with the same exercises as in GP.
	Muscular endurance		• 5-10 series of 6-12 repetitions with relatively short rest (1 min) between sets. Typical session: 10 x 10 repetitions of chins with start every minute or series of 1-2-3-4-5-6-7-8-9-10-9-8-7-6-5-4-3-2-1 start every minute.
	Core stabilization		• 20-50 repetitions of different exercises targeting core stabilization or 45/15 s work/rest in 20-30 min using different exercises involving red core (slings), Olympic rings, elastic bands and medicine balls.
	Sprints	DP	• 10-15 x 10-15 sec maximal effort typically during long-distance LIT sessions with 2-3 min active recovery between sprints. • 4-9 x 15-45 sec at 90-95% of V_{max} 2 min recovery and 5 min series breaks after repetition 3 and 6.

LIT, low-intensity training; MIT, moderate-intensity training; HIT, high-intensity training; All, unspecific training, classic skiing with kick wax, classic skiing on roller skis, skating, running, running with poles; DP, double poling, Diag, diagonal striding h, hours; min, minutes; sec, seconds.

Table 5: Representative examples of training weeks across the annual season for long-distance XC skiers

Day	Summer (GP)	Autumn (SP)	Winter (CP)
Mon	**M:** LIT long distance unspecific and specific 2.30-4 h **E**: 1-1.5 h unspecific when short and specific morning training	**M**: LIT long distance specific 2.30-4 h, including short sprints **E**: 1-1.5 h unspecific when short and specific morning training	**M**: LIT long distance skate or classic skiing 2-4 hours, often including short sprints **E**: Rest
Tue	M: LIT long distance unspecific and specific 3-4 h, including short sprints **E:** Rest	M: LIT long distance unspecific and specific 3-4 h, including short sprints. **E:** Rest	M: LIT long distance unspecific and specific 2-4 h, including short sprints **E:** 1 h unspecific when short and specific morning training
Wed	**M:** MIT intervals specific 5 x 10 min, 6 x 8 min 1-2 min break, including 30 min warm-up and short cool down 2 h **E:** Rest/strength 1 h	**M:** MIT intervals specific 5 x 10 min, 8 x 8 min, 45/15s 1-2 min break, 45-75 min total, including 30 min warm-up and short cool down 2 h, and combination **E:** Rest/strength 1 h	**M:** MIT intervals unspecific running on treadmill, 7 x 7 min, 8 x 8 min, 5 x 10 min or progressive intervals. 1-2 min break, 45-60 min total, including 30 min warm-up and short cool down 2 h **E:** Rest/strength 1 h
Thu	**M**: LIT long distance unspecific (running) and specific 2-3 h. **E:** Rest	**M:** LIT long distance unspecific (running) and specific 2-4 h. **E:** Rest	**M:** LIT long distance specific 2-5 h **E:** Rest
Fri	**M:** LIT long distance specific 2-4 h, including short sprints **E:** Rest	**M:** LIT long distance specific 2-4 h, including short sprints **E:** Rest	**M**: LIT long distance unspecific specific and combination 3-5 h **E:** Rest
Sat	**M**: MIT intervals unspecific and specific typical 6 x 5, 5 x 10 min or 10 x 3 min 1-2 min break, including 30 min warm-up and short cool down 2 h E: Short long distance unspecific and/or strength	**M:** MIT/HIT intervals unspecific (running with poles) and specific typical 6 x 5, 5 x 10 min or 7 x 4 min, 2 min break, including 30 min warm-up and short cool down 2 h, and combination **E:** Rest	**M:** MIT/HIT intervals unspecific (running on treadmill) typical 6 x 5, 45/15s min or specific 1 h continuous MIT, 2 min break, including 30 min warm-up and short cool down 2 h **E**: Rest
Sun	**M:** LIT long distance unspecific (running) and specific 2-3 h. including short sprints **E:** Rest	**M**: LIT long distance unspecific (running) and specific 2-3 h. including short sprints **E:** Rest	**M:** LIT long distance specific 2-4 h. including short sprints and combination **E:** Rest
Total	20-22 h	21-24 h	20-24 h

GP, General preparation period ; SP, Specific preparation period ; CP, Competition Period; M, morning training; E, evening training; LIT, low-intensity training; MIT, moderate-intensity training; Specific training, double poling on skis, roller skis or ski ergometer; Unspecific training, classic skiing with kick wax, classic skiing on roller skis, skating, running, running with poles; Combination, long-distance training in combination with strength, interval or continuous MIT; Rest, most long-distance skiers rest once a day, CP week is in a period without important competition, and the intention is to reload some endurance training volume.

Table 6 provides insight into the LDS skiers' specific and individual training methods, exercise mode and contents based on in-depth interviews. The weeks in CP with important competitions is characterized by significant individual variations and needs, including adaptions to former training periods, training volume, competitions results and shape.

Table 6: Summarized verbatim quotes from the training of 3 long distance XC skiers

	Spring/Summer training	Autumn	Winter and competition season
LIT	I typically perform the low-intensity sessions as either 2-8 hour double pooling sessions or 3-4 hour running sessions. Sometimes I use a mix of 2-hour double poling followed by running.	I typically implement more specific double poling sessions at higher speeds and intensity during the autumn.	During the winter, I use the skating style more instead of running. I also implement more sessions of shorter duration (1-2h). I'm more precise regarding intensity control on the long sessions during the taper.
MIT	I regularly executed 3-5 times 15 min, or eight times 8 min, double poling interval sessions in flat and uphill terrain. I also implement alternative sessions for variation and fun, such as running, orienteering or a football match.	The autumn training contained much of the same interval sessions as in the summer. However, the speed and intensity become higher towards the competition season.	We trained shorter threshold sessions in the skiing season, shorter intervals 3-8 min. The intensity around the anaerobic threshold is predominant in the competitions, but there is a need for more speed in training, so we performed shorter and faster sessions without so much lactate.
HIT/Anaerobic	The competitions and test races, running, running with poles or roller skiing were mainly the hard training sessions. We also used intervals, typically, 4-5 times ten min. as 40/20 sec. to execute long intervals at a higher speed, it was no anaerobic training.	Usually, this was the competitions and test races, running, running with poles or roller skiing intervals, typically, 5-8 times 3-7 min.	Competitions or running intervals on treadmill 5-6 times 4-6 min, we did this to keep up maximal aerobic capacity and recover the arms after the long races. Our pre-race routine was three times 3-2-1 min. in varying terrain, I4.

Strength	I typically used 4-7 specific strength exercises; Chins variations, lying bench pull or pullover, sitting and standing cable pull-down variations, dips variations and some form of squats. In addition, I use stabilization and core exercises 1-2 times of 1 h. per week	It is Essential to build strength in the arms and stabilise/core muscles to tolerate many hours with specific double poling. It is important to be ‘strong enough, and this was when I managed to do ten chins every minute ten times	I maintain my strength by performing some short maximal strength sessions. Much of my strength is maintained through the double poling in the uphill sections of the tracks and the short sprint training.
Specificity	I perform 20-50% of my training as double poling and implement a training camp on snow.	The amount of double poling training is increased during the autumn. Sprints are often implemented during long double poling sessions to simulate accelerations during competitions.	Typically 40-60% of the time, I was double poling. But on snow, we often used "nonspecific" mode like classic skiing with kick wax and skating to recover.
Sprints	We mainly included sprints on roller skis double poling in the long-distance slow session. 9-12 times 10-15 sec. max	We did this as for the spring/summer training	On snow, I executed shorter sprints 5-10 sec, max. 20 double poling strokes in uphills but with long movements.
Combination training sessions	We did all types of combinations, but we always intend to simulate the competitions or muscular load in the competition **a**) 1-2 h. long-distance slow and 1 h. MIT interval. **b**) Continues MIT 30 min - long-distance slow 1-2 h. - 45-60 min. threshold interval, total 2.30-3 h. **c**) alternating threshold and high-intensity interval in one session. Double poling. **d**) Combinations of long-distance slow 2-3 h. and continuous Threshold 30-60 min. Combinations of long-distance slow 1-2 h. and strength training 1 h and 1-2 h. long-distance slow.	We executed much of the same combination sessions, but the characteristics of the most important competitions of the year were used to design the sessions, e.g. if the goal was to win the Marcialonga, a designed specific training session could be 30-40 min. Threshold without warming up, 2.0-2.30 h. long-distance slow, and finally 15-20 min. high-intensity uphill double poling.	In the competition seasson very few combination training sessions was executed

Periodization	We didn't use traditional periodization, but we trained as much volume as possible without getting injured or overloaded, Athlete A trained seven days and rested 1 (7:1), and Athlete B used a 5:2 system but 25 h. in these five days. Athlete C used trained volume for three weeks (±75 h.) and one week 5-15h. Holidays served as restitution periods.	No periodization, as for the summer, but usually, we reduced volume towards the competition season.	Low weeks contain 10-15 h. In high weeks, we trained 20h and even up to 30 h., but only in weeks without significant competition. The intention was to preload some volume of endurance training to maintain the shape throughout the season and be able to perform in the last races.

LIT, low-intensity training; MIT, moderate-intensity training; Specific training, Double poling on skis, roller skis or ski ergometer; Unspecific training, classic skiing with kick wax, classic skiing on roller skis, skating, running, running with poles; Combination, long-distance training in combination with strength, interval or continuous MIT; Rest, most long-distance skiers rest once a day; h, hours; min, minutes; sec, seconds; max, maximal; I1-I5, intensity scale of Olympiatoppen.

Study III:

Specific aims and procedures

Study III compared performance, physiological and perceptual responses between DP and diagonal stride on steep uphill inclines and investigated the effects of pole length during DP. The athletes were evaluated while performing four identical tests, one in the diagonal stride, and three in DP with different pole lengths (self-selected, self-selected -5 cm and self-selected +10 cm). Each test was conducted at a fixed speed (10 km/h), with inclination rising by 1%, starting at 7%, until voluntary exhaustion.

Main Results

Regarding heart rate and oxygen uptake under the four different conditions, a significant effect of condition (F =189.6, $p < 0.001$, η2 = 0.87) and an interaction effect (F = 8.3, $p < 0.001$, η2 = 0.74) were found for oxygen uptake (Fig. 15). For heart rate only, a significant interaction effect (F = 1.8, $p = 0.042$, η2 = 0.38) was found. Long poles required lower oxygen uptake for DP than shorter poles at all inclinations (range 5.0-3.25 ml·min-1·kg-1 from 7-13%) and lower oxygen uptake in diagonal stride compared to DP with short poles on inclines steeper than 9% (0.9-7.86 ml·min-1·kg-1 from 8-13%). From 10% inclination, oxygen uptake was also lower in the diagonal stride compared to the self-selected and short poles, while from 12%, oxygen uptake was also lower than with DP with long poles (range 2.60-4.25 ml·min-1·kg-1 from 12-14%; Figure 15). Furthermore, from 10% inclination, heart rate was significantly (p >0.019-

0.051) lower during diagonal stride and DP with long poles compared to the other two DP conditions. Peak heart rate (F = 22.2, *p* <0.001, η2 =0.76) and peak oxygen uptake (F = 6.1, *p* = 0.004, η2= 0.47) were significantly higher in the diagonal stride test compared with the three DP conditions at complete exhaustion (Fig. 14).

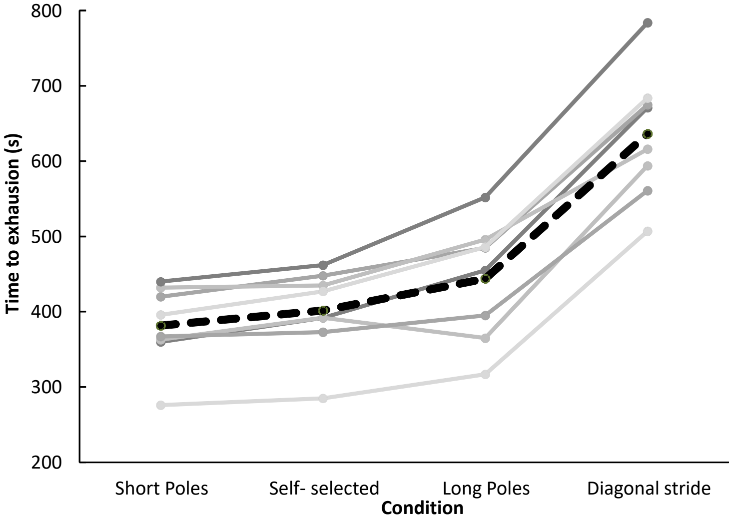


Figure 14: Individual time to exhaustion in each of the four skiing conditions and average for all participants (broken line)

TTE varied significantly between all four conditions (F = 135, *p* <0.001, η2 = 0.95), i.e. short, self-selected and long poles DP and diagonal stride, in order from the shortest to the longest TTE (Fig. 14).

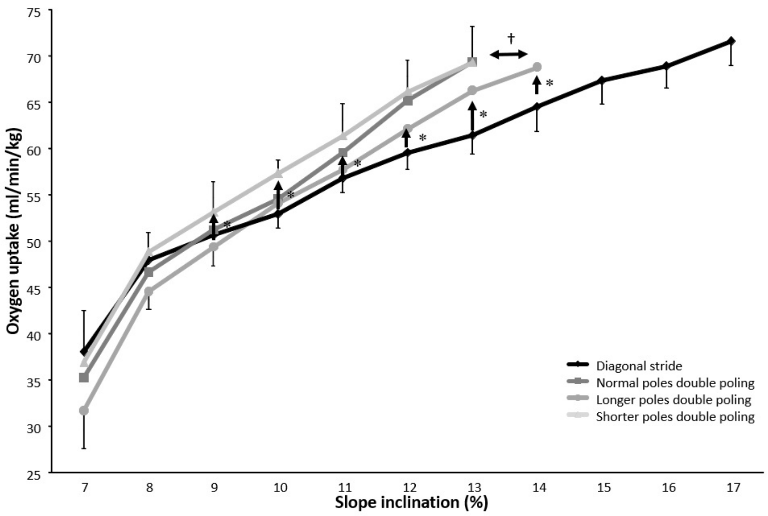


Figure 15: Mean oxygen uptake at the different slope inclinations for each of the skiing conditions. * indicates a significant difference between diagonal stride and the other conditions on the specified incline at a p <0.05 level. † indicates a significant difference at all inclinations between double poling with long poles and short poles at a p <0.05 level.

Study IV:

Specific aims and procedures

Study IV investigated the effects of pole length on physiological, kinematic and perceptual responses during increasing speed and inclination in submaximal G3 skating. All participants completed two tests while G3 roller ski skating uphill, each with three different submaximal intensities, with self-selected (SS) and long poles (SS+7.5 cm) at each intensity.

Results

For the protocol with fixed speed, VO_2 uptake was 2.7% lower (p=0.005), GE 2.1% higher (p=0.01), and the knee angle in the lowest position was 4.8% greater (p=0.05) with SS+7.5 cm than with SS at the steepest inclination of 11% (Fig. 6). For the protocol with fixed inclination, VO_2 uptake was 2.1% lower (p=0.01), GE was 4.1% higher (p=0.03), and the knee angle in the lowest position was 5.5% greater (p=0.003) with SS+7.5 cm than with SS at the highest speed of 20 $km \cdot h^{-1}$. At the lowest speed of 14 $km \cdot h^{-1}$, the VO_2 uptake was 3.0% lower (p=0.05), and GE was 3.8% higher (p=0.03) with SS+7.5 cm than with SS.

Table 7: Physiological and perceptual responses during uphill treadmill G3 roller-skiing at three 5-min sub-maximal workloads with increasing inclination at a fixed speed (10 km·h^{-1}). Kinematical responses were obtained only during the steepest inclination (N=10, mean and SD).

	7%		**9%**		**11%**		**ANOVA**		
Parameter	SS	SS+7.5	SS	SS+7.5	SS	SS+7.5	Pole length	Inclination	Pole length x Inclination
VO_2 (ml·min^{-1}·kg^{-1})	44.5 ± 1.5	44.0 ± 2.0	52.0 ± 2.1	51.0 ± 2.1	58.2 ± 2.0	56.6 ± 2.6*	$F_{1.9}$=13.27##	$F_{2.18}$=241.20###	$F_{2.18}$=1.50
BLa (mmol·L^{-1})	1.76 ± 0.5	1.68 ± 0.5	2.58 ± 0.8	2.52 ± 0.8	4.35 ± 1.1	4.32 ± 1.2	$F_{1.9}$ =0.80	$F_{2.18}$=92.05###	$F_{2.18}$=0.044
RER	0.87 ± 0.3	0.88 ± 0.3	0.91 ± 0.4	0.91 ± 0.3	0.94 ± 0.3	0.94 ± 0.4	$F_{1.9}$=0.94	$F_{2.18}$=69.10###	$F_{2.18}$=0.64
HR (beats·min^{-1})	156.7 ± 10.9	156.6 ± 11.1	173.4 ± 7.7	173.0 ± 8.2	184.6 ± 7.5	184.5 ± 7.0	$F_{1.9}$=0.19	$F_{2.18}$=158.74###	$F_{2.18}$=0.27
RPE (6-20)	9.3 ± 1.5	10.0 ± 1.9	13.1 ± 1.1	12.7 ± 1.3	16.2 ± 1.3	16.1 ± 1.0	$F_{1.9}$=0.10	$F_{2.18}$=99.62###	$F_{2.18}$=1.04
Gross efficiency (%)	17.0 ± 0.6	17.2 ± 0.8	17.5 ± 0.8	17.9 ± 0.8	18.2 ± 0.7	18.8 ± 1.0*	$F_{1.9}$= 14.08##	$F_{2.18}$=20.91###	$F_{2.18}$=0.60
Cycle length (m)					2.88 ± 0.1	2.89 ± 0.1			
Cycle time (s)					1.04 ± 0.05	1.04 ± 0.05			
Cycle rate (Hz)					0.96 ± 0.05	0.96 ± 0.05			
Knee angle (°)					126 ± 8	132 ± 7*			

SS = self-selected pole length; SS+7.5 = self-selected pole + 7.5 cm; VO_2 = oxygen uptake; BLa = blood lactate concentration; RER= respiratory exchange ratio; HR = heart rate; RPE= ratings of perceived exertion.

* Significant difference between the two pole lengths at the same inclination; $p < 0.05$.

Main effect of pole length and main effect of inclination; #$P < 0.05$, ## $P < 0.01$, ### $P < 0.001$.

Study V

Specific aims and procedures

Study V examined the effect of increased pole length (+7.5cm) on performance and choice of technique during a simulated skating XC skiing competition on snow. To compare self-selected and longer (self-selected +7.5 cm) skating poles on snow, the athletes completed two 5-km skating time trials with maximal effort. They had at least 4.5 h of rest between the two races, which were performed in a random order: one with self-selected poles (89.0% ± 0.6% of body height) and one with pole length increased by 7.5 cm (94.0% ± 0.5% of body height). Speed in set terrain sections was determined and the selection of sub-technique was self-reported immediately after each race based on a detailed review of the entire track.

Main results

The subjects in this study performed on average 7.1 ± 7.1 sec (P = 0.029) faster with the long poles, with this difference occurring solely in the uphill parts of the track (Fig. 16).

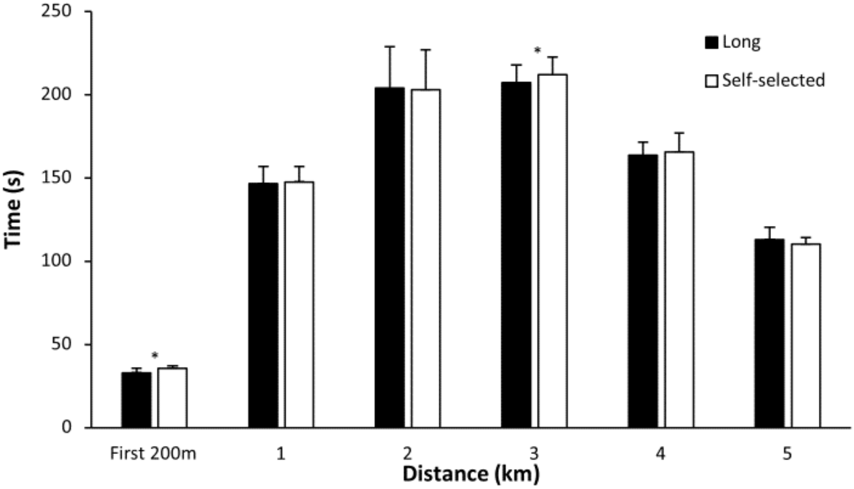


Figure 16: Pole length and performance in the five sections of the track, including the first 200 m.

The subjects in this study employed ~5% more G3 and 5% less G2 sub-techniques (both P <0.05) (Table 7). RPE was 1±0.9 points lower (P = 0.04) and skiing technique was perceived to be ~1.2±1.5 points better with long poles (P = 0.038), while physiological responses (i.e. peak and average heart rate, and blood lactate concentration) did not differ between trials.

Table 8: Reported distribution of different techniques (%) used during the 5-km cross-country race with long poles and self-selected poles, exclusive of skating without poles, tucks and turns.

	G3	G2	G4
Self-selected	66.4±20.5	19.7±10.3	14.4±10.4
Long poles	71.6±20.0*	14.9±9.1*	13.7±11.0

* indicates a significant difference between the two conditions for this sub-technique, P <0.05.

Study VI:

Specific aims and procedures

Study IV documented pole and ski lengths among elite male and female XC skiers in the classical and skating styles and investigated sex differences in body-height-normalized pole and ski lengths. An online questionnaire was distributed to all skiers participating in the Norwegian XC skiing championship 2020. Inclusion criteria were that skiers completed one distance in both classical and skating style, that they completed the questionnaire and systematically reported training in a diary. The levels of male and female skiers were relatively even, from the best performers with 0 FIS points to the lowest-ranked skiers having 400 FIS points.

Main results

Most athletes of both sexes used poles close to the length allowed by the FIS in the classical style, with men using slightly longer poles than women ($p<0.05$). Body-height-normalized pole lengths in skating were similar in men and women (around 90% of body height) (Fig. 17). Women used longer ski lengths relative to body height than men in both styles ($p<0.05$). Women showed moderate correlations ($r=0.43$, $p<0.05$) between body-height-normalized pole lengths and sprint performance.

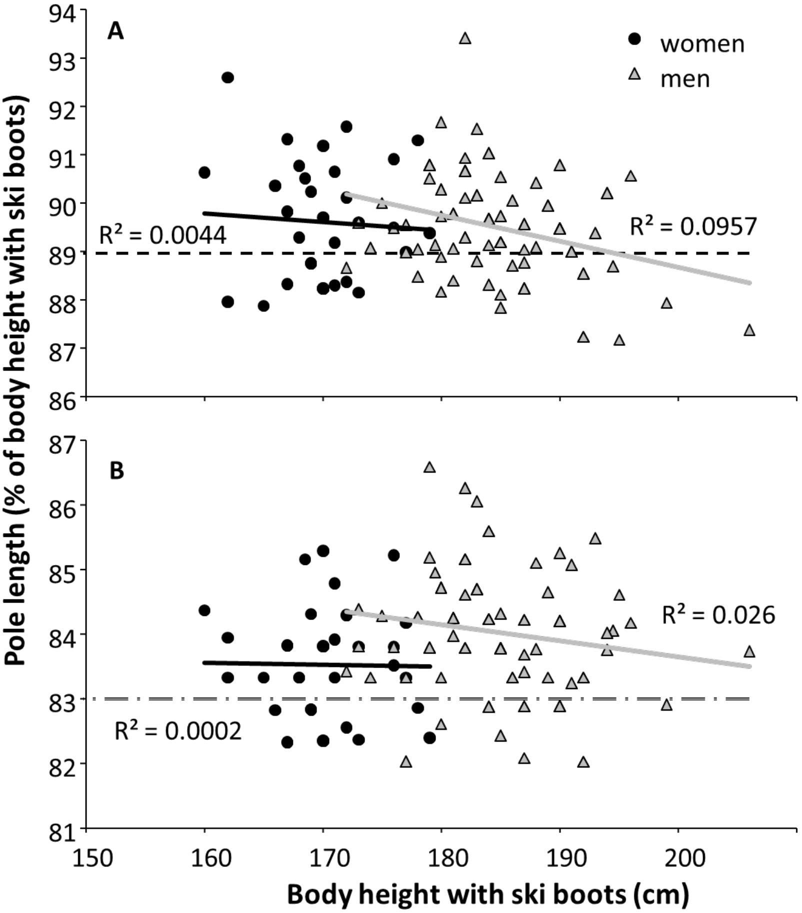


Figure 17: Pole length as a percentage of body height (using ski boots) for men and women in A) skating and B) classical cross-country skiing techniques.

- - indicates recommended pole length (89%) by the ski manufacturer

= = indicates the limit of pole length (83%) according to the FIS rules in classical ski technique

Male and female XC skiers use as long classical ski poles as possible within the current regulations, while they use skating poles similar to recommendations given by the industry (Fig. 18).

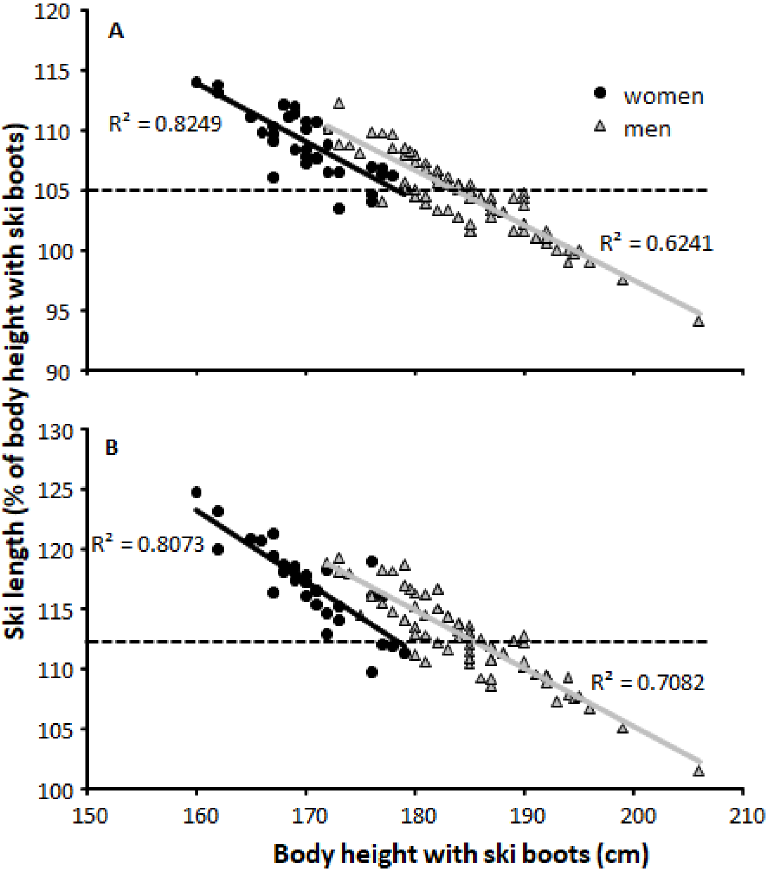


Figure 18: Ski length in relation to body height (using ski boots) for men and women in A) skating and B) classical cross-country skiing techniques.
- - indicates recommendation by the ski manufacturer

Chapter 4 Discussion

The overall objective of this thesis was to examine training characteristics and pole length manipulation for optimizing poling performance and associated physiological and kinematical capacities in long-distance and Olympic distance XC skiing.

This objective was covered by two specific aims, where study I-II aimed to physiological capacities, and kinematical patterns in DP between ODS and LDS and to describe the training characteristics of world-class LDS. Study I showed that LDS displayed a higher DP-VO_{2peak} relative to VO_{2max}, GE and peak speed in DP compared to ODS, which was followed by better ability to maintain DP technique with increasing speed. Although study II showed that the main emphasis in the training of world-class long-distance XC skiers is similar to that previously found among ODS, some clear differences that match the specific demands of long-distance XC skiing stand out: long-distance XC skiers have longer but fewer training sessions, use a pyramidal intensity distribution pattern, while significantly more of their training time is spent in the DP technique.

The second aim was covered by study III-VI, which described the choice of pole lengths among competitive XC skiers and evaluated the effects of pole length manipulation on performance in the classical and skating style. Studies III-VI demonstrated that longer poles were superior to self-selected and/or shorter poles both in DP and G3 skating when roller skiing and when ski skating on snow. Performance benefits of increased pole length seem to be greatest in steep uphills, and were associated with altered kinematics, reduced vertical displacement of CoM and reduced oxygen cost. This is supported by study VI, which reports that the best-performing male and female XC skiers use as long classic ski poles as possible under the current regulations. In skating, similar body-height-normalized pole lengths are used by men and women, and lengths are similar to those recommended by the equipment industry.

Study I: Double poling physiology and kinematics

Performance and physiology

The main finding in study I was that LDS reached a higher peak speed in DP and achieved a higher DP-VO_{2peak} than ODS, with LDS reaching the highest DP-VO_{2peak}/RUN-VO_{2max} ratio ever reported (average of 97%). In addition, GE was higher in LDS. The large amounts of DP-specific training (Study II) are likely to have contributed to the higher DP-V_{peak} reached by LDS than ODS. This coincided with a higher DP-VO_{2peak} and higher DP-VO_{2peak}/RUN-VO_{2max} ratio (i.e. 97% in LDS versus 94% in ODS) and higher GE with no between-group differences observed in RUN-V_{peak}. These findings partly differ from those of [43] who found no difference between LDS and ODS in DP performance using a comparable design. Consequently, the results of Skattebo et al. [43] may seem to contradict our findings. However, in Skattebo et al. [43], the groups of skiers were matched for overall skiing performance level (elite ODS versus elite LDS), while the groups in the present study were matched for RUN-VO_{2max} and overall training volume. The matching is also related to the novelty of our study, where we aimed to examine the adaptations resulting from more DP training in groups with similar VO_{2max} and the same level of comprehensive training. In Skattebo et al. [43], ODS achieved higher RUN-VO_{2max} and DP-VO_{2peak} than LDS, although with similar DP-VO_{2peak}/RUN-VO_{2max} ratios observed between groups. Despite this, DP performance of LDS was identical to that of ODS. Thus, independent of the different matching between groups, the data of Skattebo et al. [43] and the present study indicate that extensive DP-specific training improves DP performance beyond what may be expected based only on DP-VO_{2peak}.

The ability to reach high VO_{2peak} values depends on athletes' ability to generate power within that specific modality. Therefore, the amount of muscle mass engaged in DP [4] determines the upper body's ability to generate power and is likely to affect the level of DP-VO_{2peak}. The fact that skiers can reach more than 90% of their RUN-VO_{2max} during DP further demonstrates that DP involves whole-body work [99, 103, 109, 110]. The limit for reaching VO_{2max} in the upper body is likely to be related to longer diffusional distances, shorter mean transit times, and lower oxidative capacity in the upper than the lower body [78, 110, 111]. Upper-body muscles are reported to extract ~10% lower O_2 than leg muscles [78] and contribute, together with lower vascular conductance [112], to lower VO_{2peak} values in DP compared to running [34]. Recently, Berg et al. [113] found higher mitochondrial respiration in the upper body but equal in the lower body when comparing XC skiers with physically active controls. It may be hypothesized that the average DP-VO_{2peak}/RUN-VO_{2max} ratio of 97% among LDS in the current study, which to our knowledge is the highest ever reported in the literature [14], is due to periods with more than 60% of DP-specific training (study II) in LDS, which may further increase O_2 extraction and enhance mitochondrial respiration in upper-body muscles beyond what has previously been shown. In support of this, we additionally found small differences between LDS and ODS in body composition and maximal upper-body strength, where LDS had more muscle volume in the upper body and arms. Accordingly, the more DP-specific training by LDS may improve aerobic energy delivery, leading to a higher DP-VO_{2peak} and thus better DP performance. Alternatively, their technical ability to produce high speed and power enabled them to utilize much of their VO_{2max} during DP.

The higher GE and lower oxygen cost in LDS than ODS during submaximal DP agree with the findings of Skattebo et al. [43], who found lower oxygen cost in LDS than ODS, but smaller differences in GE (17.2% for ODS versus 17.9% for LDS at 252 W). This discrepancy in GE can partly be explained by the higher work rate of LDS than ODS in our data, due to higher body mass in our LDS, because of the non-zero offset of the metabolic rate/work rate relationship [114]. Our findings on oxygen cost and GE during submaximal running further support this point, these values also being somewhat better for LDS than ODS. However, the group differences are larger for DP than for running, demonstrating an effect beyond what can be explained by work rate. Also, although oxygen cost (values relative to body mass) suffers from the same problem with ratios, these values are more easily interpreted as body mass is transported against gravity in our protocol as well as during XC skiing races. Altogether, this shows that the superior DP ability in LDS is associated with high DP efficiency, which might be more important than VO_{2max} for long-distance races containing mostly DP, e.g. Vasaloppet [43].

Kinematics and EMG

In view of the extensive DP-specific training performed by LDS (Study II), we hypothesized that better GE and performance in DP by LDS than ODS would coincide with differences in the kinematics of DP. However, we found no differences in cycle length or rates between LDS and ODS to support these findings. This is similar to the findings of Skattebo et al. [43]. However, although most variables were similar between groups, we found some clear differences: Our data indicated that LDS maintained more effective technical patterns at higher speeds, as indicated by the significant interaction effects for pole angle at touchdown and maximum knee and hip flexion angles during the poling phase, implying that LDS maintained a more upright body position with more vertically angled poles throughout the poling phase. This was followed by higher peak and average EMG amplitudes in rectus abdominis in ODS than in LDS, with a similar pattern in biceps femoris. It seems that various small but important kinematical differences may help LDS to achieve higher peak DP speed and efficiency compared to ODS. All these differences have been previously linked to DP performance [44, 115]. However, this study was done as a relatively short test in a laboratory setting, and future studies should further examine such differences after long-duration work that mimic long-distance competitions to a greater extent.

At all speeds, we observed a trend towards LDS displaying longer poling times than ODS, but with only a minimal difference in the time available to generate force (+0.02 s for LDS, p~0.200, g_s~0.7), which could reduce the percentage of 1RM needed to perform the DP motion [76]. Further, the use of more vertically planted poles has been described as a preferred strategy of elite skiers to achieve a more dynamic and explosive poling phase in which body mass is used effectively to increase pole force [55, 116] and control of speed [117, 118]. As speed increased, we found that LDS were able to maintain pole angle at touch down at ~83°, while for ODS this angle decreased towards 79-80°. The related distance between pole tip and toe at touch down increased from ~35 cm to ~55 cm from 12.5 to 19.5 km/h^{-1} in LDS and they were able to maintain this distance up to around peak speed, while ODS increased this distance up to ~47 cm at 19.5 km/h^{-1} and then it dropped clearly to around peak speed (~43cm at 21 km/h^{-1}). At faster speeds, the ability to place the poles in such advantageous positions seems to be important and may be a limitation for ODS because of the inverse relationship between muscle contraction velocity and force, as short poling times may influence the ability to create force and power [119, 120].

DP kinematics in terms of joint angles also appeared very similar in both groups (Fig. 10). However, group and speed interaction effects were found for knee and hip angles at touch down and minimum hip angle during the poling phase. These differences probably lead to the significant interaction and minor group effects on minimum CoM height (Fig. 9), with LDS lowering their body less than ODS at faster speeds. Although the "high hip, high heel" DP strategy and thus considerable heightening and lowering of CoM is a characteristic of modern dynamic DP [55, 117], it must be executed effectively to enable body mass (gravity) and active use of trunk flexion muscles (e.g., rectus abdominis) to increase pole force. At the same time, this strategy seems to require some CoM lowering, and the finding that LDS appear to lower their CoM less than ODS agrees with the finding of [44], who found that this amount of CoM lowering depended on overall XC skiing level. This may be related to minimizing the amount of work required to heighten and reposition the body, done mainly during the recovery phase [44, 117]. Overall, these findings suggest that the LDS were able to maintain a slightly more upright body position throughout the cycle, which may explain their lower rectus abdominis activity at most speeds. Thus, if skiers cannot maintain an upright body position that enables the poles to be more vertically planted, they might be forced to use trunk flexion muscles more. However, exactly how much this difference matters remains to be examined more closely.

Overall, EMG amplitudes patterns were very similar between groups. Increasing speed led to a larger increase in $nEMG_{avg}$ in the core and lower extremities than in triceps brachii and latissimus dorsi, which agrees with previous findings of on-snow DP [121]. However, there was a clear difference in rectus abdominis and biceps femoris EMG amplitudes between LDS and ODS, where LDS performed standard sub-maximal workloads with a lower percentage of EMG amplitudes. The higher EMG activation in rectus abdominis and biceps femoris is in line with the kinematic findings, where ODS lower their CoM more than LDS. The greater rectus abdominis activation leads to greater flexion of the upper body (lower spine), and biceps femoris acts as an antagonist to this movement. Since biceps femoris flexes the knee and extends the hip joint, its activation in DP helps to avoid the unfortunate "sitting" position caused by the strong hip flexors and controls the lowering of CoM. Whether the lower peak EMG amplitudes in ODS is explained by lower DP-V_{peak} or is related to technical solutions around DP-V_{peak} remains unknown and must be examined further. Several studies have argued that higher vertical displacement of CoM results in higher oxygen cost in DP [31, 33]. This indicates that ODS use relatively more rectus abdominis and biceps femoris activation, which costs more energy. Since the rectus abdominis and the biceps femoris play an essential role in propulsion in DP and elite ODS, due to fatigue in these muscles it may compromises their ability to follow LDS in the last part of the long-distance events. This is also in line with the findings of Bojsen-Møller et al. [122], who reported significantly greater core muscle and hip flexor activity when speed was increased in DP. Note that in Study I in this thesis, ODS worked at higher % of their maximal speed when EMG was tested. This might have led to the higher EMG activity in these muscles. The core muscles contribute to external work and forward propulsion, and also use much energy for postural stabilization and repositioning of the body between each poling action. The lower EMG amplitudes in the central DP muscles at standard sub-maximal speed may also be a reason for a higher GE in LDS. This finding agrees with previous literature on EMG amplitudes in DP [55, 123].

Study II: Training characteristics of specialized long-distance cross-country skiers

The high training volume in LDS, i.e. 861 ± 90 h of training overall, including 795 h (92%) of endurance training, is in line with ODS [9, 73, 102, 124], and this high-volume, low-intensity training (88-91% of the endurance training) model in ODS is considered to provide an important foundation for long-term endurance adaptations, by increasing tolerance of extensive training without being injured or overloaded, as well as to adapt training at higher intensities [125, 126]. Furthermore, these high volumes of specific endurance training seem curtail to perform in the long lasting VSC tournament (Fig. 19)

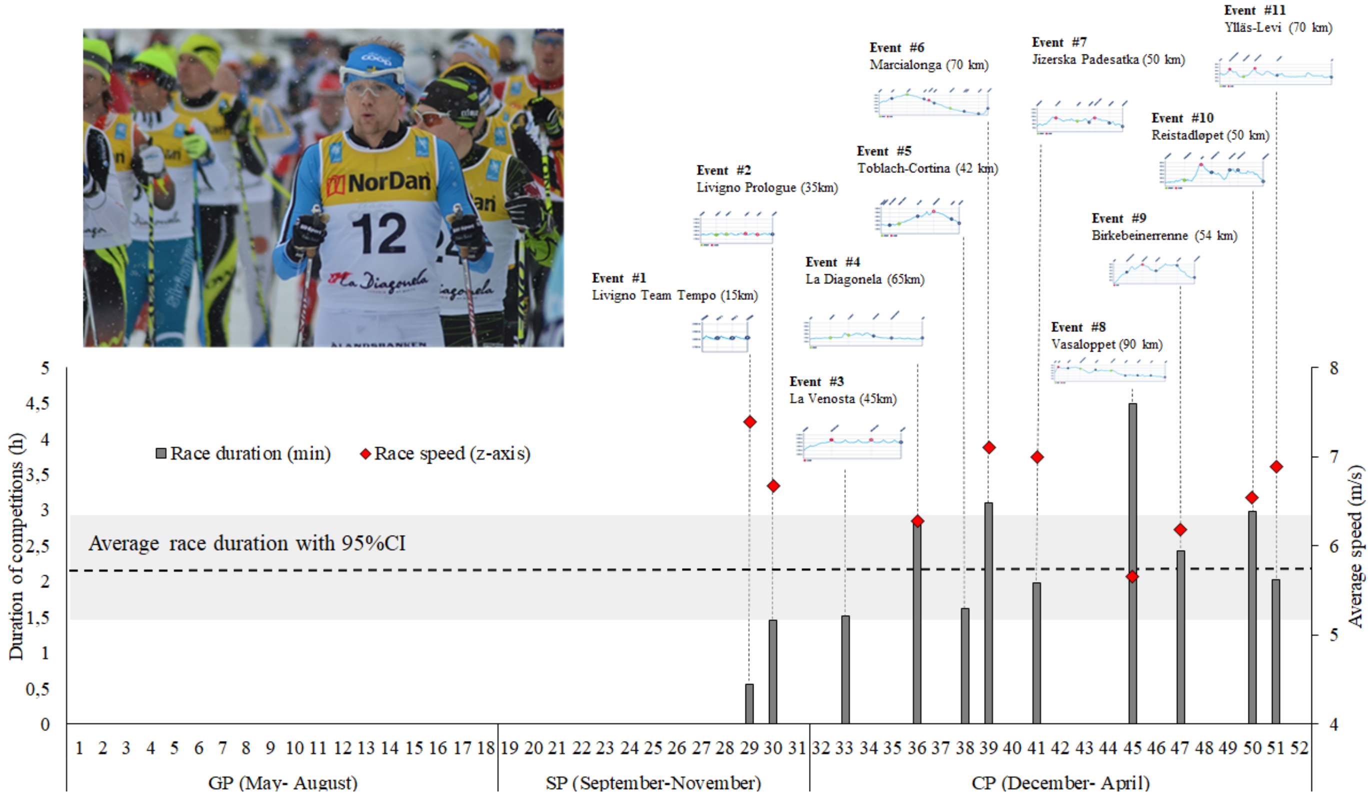


Figure 19: Illustration of the annual cycle in long-distance XC skiing, with the timing and speed of the competitions in the Visma Ski Classic. Competition duration and speed are calculated based on the average for the three best skiers in each race, and the course length and profile is reported in the official result lists (www.vismaskiclassics.com) of the 2018-20 seasons. *The Livigno Team Tempo is excluded from calculating average race duration (dotted line) with 95% CI (grey area). * The duration of the races varies a lot due to the skiing conditions, e.g. with the same calculations as above, the average time in Vasaloppet 2020-22 would have been 3.30 h. The pictures show Oskar Svärd, one of the pioneers in LDS and three times winner of Vasaloppet, at the start line before the mass start in La Diagonella

However, the pyramidal intensity distribution in LDS differs from the reported training in ODS, who often show a more polarized intensity distribution [2, 8]. This may reflect differences in competition demands, like more even terrain as in marathon running, with workloads around the anaerobic threshold [127]. This is in contrast to ODS who rarely spend more than 70 seconds in one technique and the same terrain-segment of the track [14].

Since Olympic events are of shorter duration and include an interval-based fluctuation in work rates, the metabolic energy demands in the most discriminating terrain (uphills), the workload are well above the capacity to deliver energy aerobically, and more similar to HIT sessions [12, 14, 128]. By contrast, most long-distance races are performed with DP, and the discriminating sections for LDS start at distances where Olympic races end, which makes the work rates lower and closer to the anaerobic threshold and highlights the importance of oxygen utilization and a high GE in DP. Results from Stöggl et al. [129], shows that the mean race intensity in long distance XC races was 82% of maximal heart rate. These specific demands in XC races over 2 h, using entirely DP, results in training routines consist of relatively high training volumes (i.e. >850 h/yr), with a pyramidal endurance intensity and most of the hard training sessions at the MIT level for LDS.

While the ODS performed regular HIT sessions both in the General, Specific and Competition period, the LDS executed weekly one to two MIT sessions during GP and SP, while in CP it was mainly included in competition-free weeks. The LDS reported that HIT sessions mainly comes from the imitation training when running with poles, test competitions designed to simulate the competition demands in GP and SP, in addition to HIT sessions implemented to maintain maximal aerobic power in CP. The athletes explained in the interviews that to recovery of the arms and upper body, HIT sessions were prioritized as running on treadmill in competition free weeks in the CP. While the MIT sessions in GP, SP and CP were performed using DP, either with long intervals (8-15 min) with short breaks (1-2 min) or as continuous 45-75 min sessions. Such sessions aim to delay the duration-related fatigue, reduced coordination, which directly or indirectly affects the ability to maintain muscle power throughout the entire long distance races [130].

An example highlighted in Study II was an LDS who mainly focused on Vasaloppet prepared for the race by starting many sessions in the GP and SP like the work demands in Vasaloppet. One-hour uphill DP at MIT work intensity, followed by two hours of LIT, before finishing with 30-40 min of HIT intervals. Other LDS describe similar approaches to specialize themselves for winning the Marcialonga by finishing long LIT training sessions with a 15-min steep uphill DP session, preparing themselves for the 3 km final uphill finish in this LD race. Both examples show how the LDSs MIT/HIT session designs are guided by the competition demands.

However, some regular HIT sessions were executed to increase participants' maximal aerobic power, represented by short intervals from 45 seconds to 5 min with 15 s to 3 min recovery periods. These sessions were often in a "non-specific" training mode designed to stimulate the cardiovascular system. All skiers in the present study were former ODS and had a history of training for Olympic XC skiing and earlier have measured an average VO_{2max} of ~80 $ml \cdot min^{-1} \cdot kg^{-1}$ as an Olympic distance skier. The previous focus on Olympic XC skiing has developed a high maximal aerobic power [1] that can partly be maintained with the reduced amounts of HIT in LDS when specializing in long-distance XC skiing. The shift in training routines, including greater focus on long-duration LIT and MIT sessions, may have been an positive stimuli to develop aerobic endurance and a basis for enduring the very specialized upper body training for LD XC skiing.

The periodization of this training load, including the distribution of LIT, MIT, and HIT, was relatively evenly distributed in GP and SP, with an overall reduction of training volume during CP. However, all skiers had a distinct periodization pattern in the CP, where training weeks of 20-25 h were followed by competition weeks with ~50% reduction of training load and less strain on the arms and upper body to ensure muscular fitness for the LD races.

Interestingly, more than 50% and in periods over 60% of the XC training of the LDS was performed entirely with DP, compared to ODS, who perform 50-60% of their endurance training in specific XC modes, including 11 different sub-techniques in both classical and skating styles [125]. Consequently, LDS specific training routines consisting of ~400-550 h/yr with entirely in DP, which is probably more than volume ODS performed by spent in their specific training mode.

The high amount of specific DP in LDS benefits their movement-specific endurance capacity in the upper body and DP technique in all types of terrains and speeds. Consequently, Sagelv et al. [42] and Skattebo et al. [43] demonstrated higher performance and DP efficiency, despite equal or lower VO_{2peak}, in LDS compared to ODS. In addition, previous studies by Calbet et al. [78] has shown that O_2 extraction in the XC skiers upper body approaches the level of the legs.

The high training volume in specific DP mode in LDS may further develop the upper body potential to extract O_2.

Interestingly, many of these DP sessions were relatively long (3-5 h) equal to the competition duration and therefore continued where the ODS ended their LIT sessions. Some LDS reported having performed LIT sessions as long as eight hours. In addition, LDS being specific to the demands of long-distance XC skiing, these extended LIT sessions may provide an essential adaption to prevent mechanic muscular fatigue like described in the last part of a marathon [131]. Similar approaches have been used for decades by cyclists [132]. However, it is limited how much DP volume an LDS can tolerate, and as one LDS in this study stated: "*It is also a question of how much DP you can endure, without having motivational problems, injuries, or other setbacks*". The underlying mechanisms leading to better ability to sustain long-term endurance work and prevent early fatigue in LSD might be related to improved neuromuscular function and/or enhanced fiber type transformation or better aerobic function in working muscles. However, this needs to be confirmed in future studies.

Strength and speed training complement this large amount of endurance training, and might be beneficial through several mechanisms such as maintaining muscle mass, improving work economy/efficiency, and delaying fatigue during long-distance DP [133]. However, only a certain level of strength is required, as one of the athletes stated: "*The goal of strength training is to become strong enough*". Several LDS pointed out: "*It is importance of building up their strength early in their annual training cycle to become strong enough to tolerate all the DP without getting injured".* In this context, the total volume of strength training (6%, 53 h) reported is in line with that of ODS, whereas less speed training (2%, 13 h) was reported in these LDS compared to previous data on ODS [125].

Generally, LDS placed strength training sessions in their schedule based on the purpose of the session, e.g. strength training performed after an LIT session aimed to fatigue the upper body muscles with long LIT before mobilizing the specific muscles with strength exercises. The target in other sessions was to develop movement-specific power, thus taking place directly after warm-up. Regarding the type of strength exercises, the athletes agreed that upper-body and core exercises aimed at developing power in the DP movement were most important, with chins as an example of an exercise used by all athletes.

Sessions that mainly focus on speed training were not a high priority among long-distance specialists, but all participants in the present study reported having regularly included 5-10 short sprints, performed as part of their LIT sessions. Such sessions aimed to provide them with spurt capacity during attacks or when fighting for victory at the end of a race. Therefore, these sprints are often performed at the end of LIT sessions. However, other aspects have a higher focus in their training and most of the study participants ranked their final sprint ability as relatively low. The reason for not giving greater priority to spurt capacity is interesting and depends on many factors, but as some of the skiers stated: "*Each of these long races has its own life and there are so many things going on, and it doesn't help to have a good spurt if you aren't able to follow to the sprint and are in position when the spurt starts"*. However, the reason for not prioritizing sprint ability's may be that half of the LDS in this study had participated in WC sprint skiing events at a world class level and could profit from previous training aimed for performing in sprint events.

Study III: Effects of pole length manipulation on performance in classical style XC skiing

The main finding of study III was as expected: diagonal stride showed significantly longer TTE in roller skiing in steep terrain than DP with all pole lengths. This difference coincided with lower oxygen uptake at all inclinations above 10% and higher VO_{2peak} than in DP. TTE differed significantly between all four conditions, shorter poles, normal poles and longer poles in DP, and diagonal stride, in order from shortest to longest TTE. This was reflected in lower oxygen cost for long versus self-selected and short poles without any difference in heart rate and oxygen cost across conditions.

Maximal performance was higher in roller ski diagonal stride than in all pole conditions. This contrasts with practice on snow in XC races, where many skiers only use DP. This was, however, expected since we tested the skiers on roller skis with brakes that prevented them from slipping on the treadmill. Furthermore, DP is without propulsive force in the gliding and repositioning phases. The phases without propulsive force must be reduced in the total time of a cycle on steep hills, since gliding after poling would rapidly decrease speed [5]. The roller ski brake reduces the need for vertical force to prevent the skis from slipping when performing the classic kick; more of the total power output can be used in an efficient forward propulsion, giving lower oxygen cost and improved performance. During diagonal stride uphill on snow, skiers will need considerable up and down movement of CoM to create sufficient vertical force to press the grip wax into the snow and prevent slipping [134]. In fact, most of the force in a diagonal stride kick on snow is used vertically; only ¼ is used for propulsion [135, 136]. Street [134] showed that at 14° inclination, the vertical component is insufficient to provide grip. Furthermore, the skier has only 0.10–0.20 s to perform propulsion against the snow [136, 137], and this becomes even harder when speed increases. These factors may explain the superior performance in diagonal stride versus DP in uphill roller skiing in this study.

The lower oxygen cost and heart rate at all inclinations above 10% confirm that diagonal stride and DP with long poles are more efficient than DP with self-selected and short poles. Holmberg et al. [4] showed a gradually increasing VO_{2peak} involving a higher muscle mass from arm cranking to whole bodywork. Our study demonstrated a clear increase in VO_{2peak} from DP to diagonal stride. This may indicate that DP does not produce enough power to tax the cardiovascular system maximally. The two factors that determine a high VO_2 are heart rate and O_2 pulse, and this study found a significantly higher heart rate in diagonal stride at maximal workload. The lower rate in DP is a response to various physiological factors not being fully activated to engage the cardiovascular system maximally [138]. The upper body has limitations in peripheral endurance capacity due to less muscle mass, more fast muscle fibers [139] and power production dependent on carbohydrate oxidation [140], which may explain the higher VO_{2peak} in whole body work and lower VO_{2peak} in DP in this study.

The longer TTE achieved by DP with long poles coincided with the findings of Losnegard et al. [33], who reported better performance (time trial) and lower oxygen costs with long poles. The novel findings of our study are the disadvantage of short poles and self-selected poles (i.e. higher oxygen cost and heart rate) compared to long poles and diagonal stride, and the fact that this is already apparent at 7–8% inclination. The gap in energy cost increases between short/self-selected poles and long poles/diagonal stride at inclinations greater than 8% (Fig. 15). The positive effect of long poles with increasing uphill inclination agrees with earlier investigations [31], but this is only seen up to 7.9% inclination [36]. The difference in heart rate between diagonal stride and long poles in DP compared to self-selected and shorter poles followed the same pattern as with oxygen cost (Fig. 15). The difference in oxygen cost with long poles versus short and self-selected poles is because the propulsion cycle is longer with long poles [36], and more force can thus be applied per cycle with the same or reduced vertical CoM displacement [31], compared to short poles. Shorter poles in DP are associated with higher poling frequency and reduced propulsive power per poling cycle [36]. This may result in higher oxygen cost with short and self-selected poles than with long poles, with increasing inclination [33]. Longer poles are also reported to have several kinematic advantages, such as a more upright working posture, reduced vertical displacement of CoM and more effective use uphill [31], which is related to lower oxygen cost.

Displacement of CoM and RoM was not measured, which must be considered a shortcoming of this study. However, several others have pointed out that less vertical displacement of CoM in uphill skiing with longer poles has a positive influence on oxygen cost [31, 141]. In DP, vertical displacement of CoM is important for propulsion and transfer of force through the poles. However, shorter and self-selected poles may cause excessive vertical displacement of CoM, thus increasing VO_2 cost and VO_{2peak}, unlike diagonal stride, where vertical displacement of CoM is relatively constant, since the goal is to increase horizontal displacement and reduce unnecessary vertical displacement [142]. Losnegard et al. [33] reported that in DP with longer poles versus shorter poles, hip RoM and vertical displacement of CoM were lower, resulting in lower oxygen cost. Furthermore, they pointed out that longer poles also resulted in a higher vertical CoM position throughout the poling phase, which is a preferred technique strategy in elite XC skiers [143]. Stöggl and Holmberg [144] showed that the vertical rise of CoM was 140% greater on uphill than flat terrain, and less vertical movement per cycle uphill would decrease oxygen cost. Based on previous findings, it was expected that diagonal stride and longer poles in DP would be more cost-efficient with increased inclination. By contrast, Hoffman and Clifford [62] found that diagonal stride was the least efficient of the sub-techniques examined. However, this study was on flat terrain, where the diagonal stride is limited by the short time (~0.15 s) available for the leg kick [136], while DP in flat terrain has the advantages of longer cycle length and movement throughout poling. This can also be observed in the present study at the lower inclinations (7–8%), where oxygen uptake with the long poles appears lower than with diagonal stride. It is important not to draw the conclusion that this effect is unlimited; Hansen and Losnegard [32] suggested a limitation to the length of the poles and an inverted U-shaped curve in efficiency between pole length and performance in DP.

By contrast, Holmberg et al. [55] explained that the lower oxygen uptake in DP was due to close locomotor-respiratory coupling, where the poling phase deforms the thorax as skiers bend down to a hip angle of 90–100°. The decreased compression of the trunk may explain why longer poles showed the same physiological development in heart rate and oxygen uptake to exhaustion as diagonal stride (Fig.15), unlike shorter poles. Further, in diagonal stride, athletes alternate using the left and right side to perform propulsion, while the remainder of the body has some recovery time between each stroke (micropauses), which gives better circulation in the muscles compared to DP. Pellegrini et al. [145] showed that these micropauses were reduced as inclination increase in diagonal stride. The response to this may be higher heart rate and oxygen uptake, as shown in study III.

However, these findings differ from practical experience from classic skiing competitions. The use of diagonal stride in uphill conditions during competitions is often replaced by DP [31, 144]. One reason for this discrepancy is the use of roller skis in this study. These have 100% grip, due to the backward blocking of the roller ski wheel. In competitions, in uphill on-snow skiing, a 100% grip cannot always be achieved. Thus, the main problem is to create enough force to press the ski wax under the ski sufficiently into the snow to obtain enough static friction to offset the increasing inclination. Only a small change in skiing conditions, normal force, or muscle force may result in slippery skis, and significantly reduce propulsion in diagonal stride. Under difficult waxing and skiing conditions, DP on-snow with normal and long poles may still outperform diagonal stride. Even if diagonal stride is effective in some parts of the track, skis without grip wax glide better, making them much faster in all the curves in a competition track. Therefore, to confirm this, future studies simulating the whole race-track should be conducted on snow, with kinematic analysis of the techniques. However, this may not be so interesting if the FIS regulations bout limits the pole length in classic style to 83% of body height and organizing double poling free zones in sufficient uphill sections of the track.

Study IV: Effects of pole length manipulation on performance in skating style XC skiing

The main findings in study IV, which focused on the effects of longer poles in the G3 skating technique, are in line with study III and other studies of longer poles in classical DP. Here, we specifically found that in DP longer poles were superior to self-selected and shorter poles in steep uphills and the athletes showed better performance, greater skiing efficiency, lower oxygen cost and heart rate during DP at the same load. However, this was the first study to examine the performance effects of using longer poles in skating. In classic, poles up to ~90% of body height reduced the O_2 cost [146-148]. The explanatory model is that DP and G3 are limited by the same physiological and kinematical constraints regarding at least upper-body work [149, 150]. The reason for a lower VO_2 uptake and a higher GE at 4% inclination and 20

$km \cdot h^{-1}$ may be the kinematical and muscular advantages of a greater knee angle found in the lowest position. Longer poles lead to a more upright posture with less vertical displacement of CoM, as reported by Carlsen et al. [148], Further, the effect of lower O_2 cost and higher GE due to longer than self-selected poles was more pronounced in the steep uphill protocol than in the high speed protocol. To produce greater propulsive force, longer poles can allow skiers to use the upper body and body mass more effectively [150, 151] and a more upright position lowers total displacement of RoM in steeper terrain [31].

The benefit of longer poles in steeper uphill terrain is interesting, since this is the most discriminating terrain and more than 50% of race time is spent there [152], and longer poles may enhance uphill performance and significantly influence the race outcome. Interestingly, even at the highest international level, skiers have not utilized the potential of longer poles approved by the FIS rules (FIS §343.8.2). Lower O_2 cost caused by longer poles cannot solely be explained by the lower vertical displacement of CoM in our study, since proven differences in CoM between long and short poles are relatively small (1 cm) [147, 148]. Vertical displacement was not measured in the present study, but the postural knee angle was significantly greater in the two SS+7.5 cm conditions at 11% uphill (4.8% greater than SS) and 10 $km \cdot h^{-1}$ (5.5% greater than SS). However, it is important not to underestimate small differences in displacement of CoM in endurance sports like XC skiing, since every movement is repeated many times. The smaller displacement of the knee extension/flexion pattern when longer poles were used may be related to the lower O_2 cost. A greater knee angle with longer poles will probably also positively influence the hip and ankle joint angles, i.e., a smaller external moment and torque in ankle, knee and hip joints, resulting in a more upright position. Longer poles may also result in a smaller forward fall and reduced RoM, which may appear disadvantageous. However, a smaller forward fall may actually reduce energy use in postural stabilization muscles around the hip and thereby reduce O_2 cost. Carlsen et al. [148], during DP in uphills, observed less forward fall and the touchdown of the poles was further back in the snow with long poles. More forward angled poles in G3, less vertical displacement of CoM, and a greater knee angle in the lowest position may produce a more effective force and result in lower O_2 cost at the same relative workload in the highest speed and steepest uphill conditions. This is supported by Carlsen et al. [148], who showed a greater forward fall in the whole body with shorter poles, both in steep and moderate uphill conditions.

The 4% and 14 km·h^{-1} conditions also demonstrated a lower O_2 cost and greater GE for longer poles. This workload is defined as intensity zone 1 (I1) and is the training intensity zone most used by XC skiers. The 4% and 17 km·h^{-1} conditions are defined as intensity zone two (I2), which XC skiers try to reduce to avoid fatigue in daily training [153]. The amount of specific training at the lowest (I1) and highest submaximal (I3) workload (inclination and speed) may partly explain the more effective use of longer poles in these conditions. Although there was no significant difference between pole length at 4% and 17 km·h^{-1}, longer poles were not less effective than self-selected ones. This makes longer poles more useful than SS in all conditions in this experiment.

During G3 skiing the cycle characteristics between SS and SS+7.5 cm was only measured at the two highest submaximal workloads (10 km·h^{-1} and 11% inclination, and 20 km·h^{-1} and 4% inclination). No significant effect of pole length on cycle characteristics was found. Previous studies [31, 36] showed that pole length affected both kinematics and kinetics in DP. Increased pole length resulted in longer ground contact times, higher propulsion per poling and reduced poling rate, which provided a more energetic and efficient poling technique. G3 skating is a far more complex technique than DP and one reason for the lack of differences may be that the leg push-off was a compensatory factor in skating, which is impossible in only DP.

The participants reported no significant differences in RPE between SS+7.5 cm and SS in any of the three submaximal workloads. This finding contrasts with anecdotes from the XC skiing community about the disadvantage of longer poles in 'the slower forward shuttle' and the aim to ski with 'low shoulders' in the repositioning phase. After testing, the skiers in this study did not give any negative feedback on the use of longer poles compared to SS. However, the translation of these results to on-snow G3 skiing was further investigated in study V.

Study V: Pole length influences performance during on-snow skating in female cross-country skiers

Our findings of better performance with long poles than self-selected poles in study V concur with those of studies III and IV, indicating that longer poles enhanced performance and reduced O_2 cost during uphill treadmill roller skiing, both with the G3 skating technique and with DP [31, 33, 34, 36]. In the present study, the effect of pole length was tested on snow using the skating technique for the first time. We found significant performance improvements with 7.5 cm longer poles compared to self-selected ones, which were mainly in the first 200 m and during the longest uphill in section 3. While the improvement in the initial 200 m may be explained by faster acceleration with longer poles, as previously shown for DP in the studies by Hansen and Losnegard [32] and Losnegard et al. [34], better section 3 performance was probably due to improvement in the longest uphill section, where skiers reported more use of the G3 technique with longer poles. The literature claims that performance in G3 as reported in the present study can be explained by the same mechanisms as previously found in DP on a treadmill [31, 33, 36, 37]. Also, longer poles resulted in lower O_2 cost, which was associated in all studies with reduced vertical displacement of CoM and longer poling time.

In study IV, we reported higher GE with long poles compared to self-selected ones in G3 skating at 11% uphill inclination and 10 $km \cdot h^{-1}$ in roller skiing on a treadmill. This supports the findings in Study V, where the skiers reported more use of G3 in uphill sections of the track (9.3% incline and average speed of 13.5 $km \cdot h^{-1}$) with longer poles. The effectiveness of using longer poles in uphill skating may be explained by a higher start position for poling and thus a more upright position with reduced vertical displacement of the CoM, as reported in Study IV. A shorter distance between CoM and poles and between bindings and pole plant in DP has also been pointed out by Carlsen et al. [31] and Losnegard et al. [34]. Notably, the enhanced performance found in Study V was found with equal physical strain, and with slightly lower perceived exertion, with longer poles.

However, it is not known to what extent lower speed or steeper incline determine the positive effect of increased pole length. Indeed, speed and incline are interrelated, and cycle characteristics and the choice of sub-technique seem to be influenced by both factors when they are isolated. However, the fact that longer poles are most effective at lower speeds, which take place at steeper inclines and at the start when accelerating from zero, indicates that low speed might be an important contributor. Because of the lower speeds among women, longer poles might be more beneficial for women than men. While Trøen et al. [37] indicated that this is also the case in the classic style, this aspect needs to be further examined in skating.

No disadvantage of longer poles was found in the final 200 m sprint towards the finishing line due to the expected slower repositioning of the poles and maintenance of frequency. In fact, the lack of experience with longer poles indicates that extensive practice with long poles may enhance performance even more. This was exemplified by closer analysis of the data, showing that the only skier who did not benefit from longer poles over the entire 5 km time trial lost 10 sec during the first 2 km. Our communication with the athlete revealed that she struggled to find the right technique for “timing” the pole plants in the first 2 km. However, this participant was also 5 sec faster with the long poles in section 3, which had the longest uphill section of the track. Additionally, the two athletes with the lowest FIS points and best performance during the time trial had the greatest effect from the long poles, with 14 and 16 sec improvements. This is not unexpected since these two skiers probably have the best potential for utilizing longer poles, with a well-developed technique and upper body capacity [154].

Despite the lack of practice with longer poles, the participants reported a significantly better perception of skiing technique (i.e. a better feeling) when skiing with longer than with self-selected poles. However, it should be noted that four of the skiers reported that one short 25-m steep uphill section 500 m from the finishing line was challenging with long poles, due to longer repositioning of the long poles in the G2 sub-technique.

Study VI: Choice of pole lengths among competitive XC skiers

As complementary to studies III-V, study VI examined how elite XC skiers actually choose pole and ski lengths for competitions in both the classical and skating styles. The majority of skiers in this study used poles close to the length allowed by the FIS in the classical style (83% of body height); this was true of both sexes, but men used slightly longer poles than women. This finding supports previous research concerning the importance of long pole length in effective DP [33]. It appears that men are more aware of this advantage than women and have found that DP can be more effective with longer poles. However, the fact that there was a correlation between performance and pole length in female sprint skiing indicates that female XC skiers also utilize this advantage of longer poles.

Body-height-normalized pole lengths in skating were around 90% of body height. Accordingly, only 1% of skiers used longer skating poles (92–94% of body height) and utilized the potential benefit mentioned in previous research by improving work economy, treadmill and on-snow performance in the G3 sub-technique (Studies III and IV). The benefits of longer poles in DP were soon applied in the skiing community but they have not yet been adopted in XC skating. However, DP is a less complex technique than G3 skating and previously the use of long poles was often associated with a negative effect on skiing technique, such as disturbance effects on skiing rhythm, lifting the arms higher, high shoulders, more tension in the arm and shoulder muscles in the repositioning phase, negative effects on the pole pendulum and slower repositioning of the poles including increased air resistance. Whether these anecdotes from the skiing community are valid, needs to further be examined in both the classical and skating style.

Women chose to use longer skis than men in both styles, and women’s skis are reported to be longer than typically recommended. Here, anecdotes from the skiing community are communicated that longer skis glide better due to better weight distribution over a more extensive nominal contact area, which is especially important in cold conditions, an advantage that is also confirmed by Breitschädel [38]. Consequently, XC women will select longer classical skis if they are soft enough so the grip wax can grip the snow to execute the classic kick. Further, the ski industry produces fewer high-quality skis for the shortest female skiers. Therefore, they and ambitious young boys and girls will compete for the same pairs of skis within the recommended length for their body size. In this case, choosing skis 5–10 cm longer gives a broader choice of high-quality skis. This is also supported by communication with the ski industry, represented by Mobakken in Rossignol Norway (technician 2021), who argues that production of skis of different lengths is mainly dependent on financial considerations. In contrast, almost all senior men use skis close to the maximum ski length produced, since the longest classical and skating skis on the market are 207–210 cm and 190–195 cm, respectively. Accordingly, ~80% of male XC skiers use the maximal ski lengths in both styles.

Methodological considerations

In general, the strengths of the present studies are the high level of the skiers participating, the combination of laboratory and field studies and the broad range of important performance factors evaluated in a complex winter sport. However, due to the small number of athletes participating in most of these studies, results should be interpreted with caution, and further studies with a higher number of athletes and a more comprehensive range of performance levels would be required to draw firm conclusions. In addition, there are specific methodological considerations for the specific studies as listed below:

Studies I-II

Seventeen world class LDS were included in studies I-II (five and twelve respectively). A problem in including top-level athletes is to determine how many can be defined as world class and how many are available for such research projects. In relation to willingness and possibility to participate, time and resources, the number of respondents was low, but the quality of the athletes was high. There was also the methodological question of how to match the LDS with the ODS. In study I, we chose to match them by VO_{2max} since VO_{2max} was a critical issue in our aims and is traditionally the single best predictor of performance in XC. Others have matched them by performance [42, 43], which was not possible since very few ODS have participated in the long-distance events. By contrast, the novelty of study II is the high number of successful world-class LDS skiers (n=12) that provided their training data since the rise of professional long-distance skiing (the past 10 years). The data were collected from their training diary through their responses to the questionnaire. Data were also strengthened by personally interviewing three of the successful LDS, and the interviews provided depth and greater understanding of the context behind the numbers. However, limitations of this methodology are related to training knowledge, quality and precision of data from training diaries and translation from diaries to responses to the questionnaire. However, such data from elite XC skiers have previously been evaluated and reported to provide a valid and accurate measurement of duration and intensity [155]. Further studies should evaluate the skiers' training background and include a longitudinal study of their development as an LDS. It would also be interesting to see how the transition from ODS to LDS is performed successfully.

Study III

The strength of this study is the involvement of different pole lengths in several classic sub-techniques and the high accuracy of the data obtained in the controlled lab conditions. However, the central methodological concern is external validity since practical experience is that DP on the entire track, with long poles and without kick wax, even today outperforms skiing in all sub-techniques and classic grip wax under the skis. Although this was not the aim of the study, the protocol might seem to be challenged by the increasing inclination and the fact that the stages were not long enough to define a steady state to calculate GE.

Studies IV and V

The vast majority of research on the effects of longer poles has been conducted in classical skiing, and the theoretical framework in these two studies therefore had to rely on findings and conclusions from pole length studies in DP. Accordingly, Studies IV and V represented a further development of Study III. Standard reliable and valid test methodology of kinematics, physiology and RPE was utilized to evaluate the effects of pole length in skating uphill using the G3 technique.

There are clear limitations to the self-reporting of techniques in Study V. Future approaches should include automatic detection of sub-techniques as implemented previously in the classical style by e.g. Seeberg et al. [156] and Solli et al. [54]. No previous studies have yet provided valid skating algorithms [85, 86]. Despite these limitations, we believe that the athletes had a sound basis for judging their use of sub-technique since all the athletes involved in this study were very familiar with the track through training there for several hundred hours and regularly participating in competitions. To increase validity, a detailed questionnaire, track map and profile were used to communicate with the athletes around their estimates of the use of skating sub-techniques in this study.

Study VI

The primary methodological limitation of Study VI is how the equipment was measured by the different brands and measurements defined by the FIS. They did not match and needed to be normalized according to models and years of production before being analyzed with traditional statistical methods. Furthermore, normalizing for body height might not be an optimal procedure since the anthropometric differences between athletes (e.g. differences in length of the head and the neck) may lead to differences in the rotation point of the shoulder between skiers with similar body height. In this context, the shoulder joint forms the basis for transferring power from the body through arms and poles. Previously, the appropriate measuring point to select both classical and skating poles was shoulder height [157]. Due to this research, Swix changed its measuring of their poles to align with the FIS rules. Future studies should examine more closely the effect of using longer poles in skating sprints and especially the start and finish of races. Studies should also investigate the consequences on technique and performance of the longer skis recommended to female skiers by the industry.

Conclusions

This thesis examined training characteristics and pole length manipulation for optimizing poling performance and associated physiological and kinematical capacities in long-distance and Olympic distance XC skiing. Studies I and II aimed to compare training characteristics, physiological capacities, and kinematical patterns in DP between Olympic distance and long-distance XC skiers. Here, study I found the highest ever reported DP/RUN-VO_{2peak} ratio of 97% in LDS, which coincided with better DP performance and ability to maintain effective technique at faster DP speeds. In addition, LDS achieved higher GE than ODS and demonstrated longer relative poling times and lower normalized EMG amplitudes in rectus abdominis and biceps femoris. The main reasons for these advantages in DP performance and physiology are probably associated with the unique training patterns described in study II. Here, data showed that the superior DP performance of world-class long-distance XC skiers was followed by high training volumes (861 h annually) with most of the training performed as low-intensity endurance training. However, some clear format-specific differences in training seem to be present: LDS train longer but fewer sessions (regular 3-5 h sessions), use a pyramidal intensity distribution pattern (88.7% LIT, 6.4% MIT and 4.8% HIT) and spend more of their training time (50-60%) on the DP technique, compared to ODS. Accordingly, the training routines seem to match the specific demands of long-distance XC skiing, with competitions commonly performed as long-duration DP.

Taken together, the combination of better DP-specific aerobic energy delivery capacity, efficiency and technical solutions that lead to the superior DP performance found among specialized LDS are reflected in their training patterns with a notable focus on DP training specifically for long-distance events.

Studies III-VI aimed to describe choice of pole length by competitive XC skiers and investigate the effects of pole length manipulation on performance in classical and skating style XC skiing. All studies showed longer poles to be superior to self-selected and/or shorter poles, both in DP (study III) and G3 skating (study IV) when roller skiing and when ski skating on snow (study V). Performance benefits of increased pole length seem to be greatest in steep uphills, and associated with altered kinematics, reduced vertical displacement of CoM and reduced oxygen cost. While these benefits have previously been indicated for DP on flat to moderate inclines, study III was the first study to show the benefits of longer poles for DP on uphill terrain, although diagonal stride was the superior technique here. Another novel finding was the superior effect of longer than self-selected pole length in G3 skating on performance and GE in uphills and at high speed at lower inclination, which was associated with a greater knee angle in the lowest position, suggesting that skiers have less vertical displacement when using longer poles. Also, during on-snow ski skating, longer poles were found to be beneficial for female skiers. Here, the performance improvement induced by longer poles occurred in the initial part of the race and the longest uphill section, which coincided with more use of the G3 sub-technique than G2. Since this took place without any changes in physiological parameters, but with improved perceived feeling and lower ratings of perceived exertion with long poles, it is suggested that the positive effects of choosing longer poles are followed by the same mechanisms as those found for DP and G3 skating. This is also supported by study VI, which reports that the best-performing male and female XC skiers use as long classic ski poles as possible under the current regulations. In skating, similar body-height-normalized pole lengths are used by men and women, similar to those recommended by the industry.

References

1. Holmberg, H.-C., *The elite cross-country skier provides unique insights into human exercise physiology.* Scandinavian Journal of Medicine and Science in Sports, 2015. **25**(S4): p. 100.
2. Sandbakk, Ø. and H.-C. Holmberg, *Physiological Capacity and Training Routines of Elite Cross-Country Skiers: Approaching the Upper Limits of Human Endurance.* International journal of sports physiology and performance, 2017. **12**(8): p. 1003-1011.
3. Bergh, U. and A. Forsberg, *Influence of body mass on cross-country ski racing performance.* Medicine and science in sports and exercise, 1992. **24**(9): p. 1033-1039.
4. Holmberg, H.C., H. Rosdahl, and J. Svedenhag, *Lung function, arterial saturation and oxygen uptake in elite cross country skiers: influence of exercise mode.* Scandinavian Journal of Medicine & Science in Sports, 2007. **17**(4): p. 437-444.
5. Rusko, H., *Handbook of sports medicine and science, cross country skiing*. 3rd ed. 2003, Malden, Massaschusetts, USA: Blackwell Publishing.
6. Saltin, B., *The physiology of competitive cc skiing across a four decade perspective; with a note on training induced adaptations and role of training at medium altitude*. Science and Skiing ed. E.Müller. 1997, London: Spon. 435–469.
7. Sandbakk, O., et al., *The Physiological Capacity of the World's Highest Ranked Female Cross-country Skiers.* Med Sci Sports Exerc., 2016. **48**(6): p. 1091-1100.
8. Sandbakk, Ø. and H.-C. Holmberg, *A Reappraisal of Success Factors for Olympic Cross-Country Skiing.* International Journal Of Sports Physiology And Performance, 2014. **9**(1): p. 117-121.
9. Tonnessen, E., et al., *The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance.* Plos One, 2014. **9** p. 101796-101796.
10. Norman, R., Ounpuu, S., Fraser, M., & Mitchell, R., *Mechanical Power Output and Estimated Metabolic Rates of Nordic Skiers During Olympic Competition.* International Journal of Sport Biomechanics, 1987. **5**(2): p. 169-184.
11. Mygind, E., L. Andersen, and B. Rasmussen, *Blood lactate and respiratory variables in elite cross -country skiing at racing speeds.* Scandinavian Journal of Medicine & Science in Sports, 1994. **4**(4): p. 243-251.
12. Karlsson, Ø., et al., *Exercise Intensity During Cross-Country Skiing Described by Oxygen Demands in Flat and Uphill Terrain.* Frontiers in Physiology, 2018. **9**(846).
13. Gløersen, Ø., et al., *Technique analysis in elite athletes using principal component analysis.* Journal of Sports Sciences, 2018. **36**(2): p. 229-237.
14. Losnegard, T., *Energy system contribution during competitive cross-country skiing.* Eur J Appl Physiol, 2019. **119**(8): p. 1675-1690.
15. Gløersen, Ø., J. Kocbach, and M. Gilgien, *Tracking performance in endurance racing sports: Evaluation of the accuracy offered by three commercial GNSS receivers aimed at the sports market.* Front Physiol, 2018. **9**: p. 1425-1425.
16. Tønnessen, E., et al., *Maximal aerobic capacity in the winter-Olympics endurance disciplines: Olympic-medal benchmarks for the time period 1990–2013.* International journal of sports physiology and performance, 2015. **10**(7): p. 835-839.

17. Norman, R., et al., *Mechanical power output and estimated metabolic rates of Nordic skiers during Olympic competition.* Journal of Applied Biomechanics, 1989. **5**(2): p. 169-184.
18. Andersson E, S.M., Sandbakk O, Sperlich B, Stoggl T, Holmberg and HC, *Analysis of sprint cross-country skiing using a differential global navigation satellite system.* Eur J Appl Physiol, 2010. **110**(3): p. 585-595.
19. Marsland, F., et al., *Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition.* PLoS One, 2017. **12**(8): p. e0182262-e0182262.
20. Sandbakk, Ø., *The Evolution of Champion Cross-Country-Skier Training: From Lumberjacks to Professional Athletes.* International Journal of Sports Physiology and Performance, 2017. **12**(2): p. 254-259.
21. Østerås, H., J. Helgerud, and J. Hoff, *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): p. 255-263.
22. Haugnes, P., et al., *The Effect of Maximal Speed Ability, Pacing Strategy, and Technique on the Finish Sprint of a Sprint Cross-Country Skiing Competition.* Int J Sports Physiol Perform, 2019. **14**(6): p. 1-795.
23. Bilodeau, B., B. Roy, and M. Boulay, *Effect of drafting on work intensity in classical cross-country skiing.* International journal of sports medicine, 1995. **16**(03): p. 190-195.
24. Sandbakk, Ø., et al., *The physiology of world-class sprint skiers.* Scandinavian Journal of Medicine & Science in Sports, 2011. **21**(6): p. e9-e16.
25. Stöggl, T.L., et al., *Pacing, Exercise Intensity, and Technique by Performance Level in Long-Distance Cross-Country Skiing.* Front Physiol, 2020. **11**: p. 17.
26. Andersson, E., et al. *Energy contributions and pacing strategies of elite XC skiers during sprint skiing*. in *ICSS 2016-International Congress on Science and Skiing, Arlberg, Austria, 10-15th December, 2016*. 2016.
27. Losnegard, T., K. Kjeldsen, and Ø. Skattebo, *An analysis of the pacing strategies adopted by elite cross-country skiers.* Journal of strength and conditioning research, 2016. **30**(11): p. 3256-3260.
28. Stöggl, T., B. Pellegrini, and H.-C. Holmberg, *Pacing and predictors of performance during cross-country skiing races: A systematic review.* Journal of sport and health science, 2018. **7**(4): p. 381-393.
29. Welde, B., 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).
30. Ainegren, M., V. Linnamo, and S. Lindinger, *Effects of Aerodynamic Drag and Drafting on Propulsive Force and Oxygen Consumption in Double Poling Cross-country Skiing.* Med Sci Sports Exerc, 2022.
31. Carlsen, C.H., et al., *Pole lengths influence O2-cost during double poling in highly trained cross-country skiers.* European Journal of Applied Physiology, 2018. **118**(2): p. 271-281.
32. Hansen, E. and T. Losnegard, *Pole length affects cross-country skiers' performance in an 80-m double poling trial performed on snow from standing start.* Sports Engineering, 2010. **12**(4): p. 171-178.
33. Losnegard, T., et al., *The Influence of Pole Length on Performance, O2 Cost, and Kinematics in Double Poling.* International journal of sports physiology and performance, 2017. **12**(2): p. 211-217.

34. Losnegard, T., et al., *The influence of pole lengths on O_2-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): p. 2579.
35. Nilsson, J., et al., *Pole length and ground reaction forces during maximal double poling in skiing.* Sport Biomech / International Society Of Biomechanics In Sports, 2003. **2**(2): p. 227-36.
36. Onasch, F., A. Killick, and W. Herzog, *Is there an optimal pole length for double poling in cross country skiing?* Journal of Applied Biomechanics, 2017. **33**(3): p. 197-202.
37. Trøen, E., et al., *Pole Length's Influence on Performance During Classic-Style Snow Skiing in Well-Trained Cross-Country Skiers.* International Journal of Sports Physiology and Performance, 2020. **15**(6): p. 884.
38. Breitschädel, F., *Variation of Nordic classic ski characteristics from Norwegian national team athletes.* Procedia Engineering, 2012. **34**: p. 391–396.
39. Ingjer, F., *Maximal oxygen uptake as a predictor of performance ability in women and men elite cross‐country skiers.* Scandinavian Journal of Medicine & Science in Sports, 1991. **1**(1): p. 25-30.
40. Larsson, P., et al., *Physiological predictors of performance in cross‐country skiing from treadmill tests in male and female subjects.* Scandinavian Journal of Medicine & Science in Sports, 2002. **12**(6): p. 347-353.
41. Sandbakk, Ø., et al., *The Physiological Capacity of the World's Highest Ranked Female Cross-country Skiers.* Med Sci Sports Exerc, 2016. **48**(6): p. 1091-1100.
42. Sagelv, E.H., et al., *Physiological Comparisons of Elite Male Visma Ski Classics and National Level Cross-Country Skiers During Uphill Treadmill Roller Skiing.* Front Physiol, 2018. **9**: p. 1523.
43. Skattebo, Ø., T. Losnegard, and H.K. Stadheim, *Double Poling Physiology and Kinematics of Elite Cross-Country Skiers: Specialized Long-Distance Versus All-Round Skiers.* Int J Sports Physiol Perform, 2019. **14**: p. 1-1199.
44. Zoppirolli C, et al., *Double poling kinematic changes during the course of a long-distance race: effect of performance level.* J Sports Sci., 2020. **38**((8)): p. 863-872.
45. Zoppirolli, C., et al., *Following a Long-Distance Classical Race the Whole-Body Kinematics of Double Poling by Elite Cross-Country Skiers Are Altered.* Frontiers in physiology, 2018. **9**.
46. Pellegrini, B., T.L. Stöggl, and H.-C. Holmberg, *Developments in the Biomechanics and Equipment of Olympic Cross-Country Skiers.* Front Physiol, 2018. **9**(JUL): p. 976-976.
47. Bolger, C.M., Kocbach, J., Hegge, A. M., & Sandbakk, Ø., *Speed and Heart-Rate Profiles in Skating and Classical Cross-Country-Skiing Competitions.* International Journal of Sports Physiology and Performance, 2015. **10**(7): p. 873-880.
48. Holmberg, H.C., *Teknik og metodik*, ed. B. CEWE-Forlag. 1996.
49. Sandbakk, Ø., et al., *Preparing for the Nordic Skiing Events at the Beijing Olympics in 2022: Evidence-Based Recommendations and Unanswered Questions.* Journal of Science in Sport and Exercise, 2021. **3**(3): p. 257-269.
50. Stöggl, T.L., et al., *Pacing, Exercise Intensity, and Technique by Performance Level in Long-Distance Cross-Country Skiing.* Front Physiol, 2020. **11**: p. 17-17.
51. FIS, *The International Ski Competition Rules (ICR: Book II Cross- Country). The International Ski Federation.* https://www.fs-ski.com/mm/Document/documentlibrary/Cross-Count ry/03/21/20/ICRCross-Country2017_marked-up_English.pdf. , 2020. Accessed May 2020.

52. Sandbakk, Ø., *The Evolution of Champion Cross-Country-Skier Training: From Lumberjacks to Professional Athletes.* Int J Sports Physiol Perform, 2017. **12**(2): p. 254-259.
53. Marsland, F., et al., *Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition.* Plos One, 2017. **12**(8).
54. Solli, G.S., 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): p. e0207195.
55. Holmberg, H.-C., et al., *Biomechanical analysis of double poling in elite cross-country skiers.* Med Sci Sports Exerc, 2005. **37**(5): p. 807-818.
56. Losnegard, T. and J. Hallén, *Physiological Differences Between Sprint- and Distance-Specialized Cross-Country Skiers.* International Journal of Sports Physiology and Performance, 2014. **9**(1): p. 25-31.
57. Björklund, G., M.S. Laaksonen, and H.-C. Holmberg, *Blood lactate recovery and respiratory responses during diagonal skiing of variable intensity.* European Journal of Sport Science, 2011. **11**(5): p. 317-326.
58. Losnegard, T., et al., *Effects of active versus passive recovery in sprint cross-country skiing.* International journal of sports physiology and performance, 2015. **10**(5): p. 630-635.
59. Sandbakk, Ø., et al., *The physiology of world-class sprint skiers.* Scandinavian Journal of Medicine & Science in Sports, 2011. **21**(6): p. e9-e16.
60. Gløersen, Ø.N., et al., *Oxygen demand, uptake, and deficits in elite cross-country skiers during a 15-km race.* 2020.
61. Hoff, J., J. Helgerud, and U. Wisløff, *Maximal strength training improves work economy in trained female cross-country skiers.* Medicine and science in sports and exercise (trykt utg.). 1999. **31(1999)nr 6**: p. 870-877.
62. Hoffman, D.M. and S.P. Clifford, *Physiological responses to different cross country skiing techniques on level terrain.* Medicine & Science in Sports & Exercise, 1990. **22**(6): p. 841-848.
63. Hoffman, D.M., et al., *Physiological comparison of uphill roller skiing: diagonal stride versus double pole.* Medicine & Science in Sports & Exercise, 1994. **26**(10): p. 1284-1289.
64. Mahood, V.N., et al., *Physiological determinants of cross-country ski racing performance.* Medicine and Science in Sports and Exercise, 2001. **33**(8): p. 1379-1384.
65. Hoffman, M.D. and P.S. Clifford, *Physiological aspects of competitive cross -country skiing.* Journal of sports sciences, 1992. **10**(1): p. 3-27.
66. Hoffman, M.D., et al., *Physiological comparison of uphill roller skiing: diagonal stride versus double pole.* Medicine and science in sports and exercise, 1994. **26**(10): p. 1284-1289.
67. Mikkola, J., et al., *Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners.* International journal of sports medicine, 2007. **28**(07): p. 602-611.
68. Millet, G.P., D. Boissiere, and R. Candau, *Energy cost of different skating techniques in cross-country skiing.* Journal of Sports Sciences, 2003. **21**(1): p. 3-11.

69. Millet, G., et al., *Relationships between aerobic energy cost, performance and kinematic parameters in roller ski skating.* International journal of sports medicine, 2002. **23**(03): p. 191-195.
70. Sandbakk, Ø., et al., *Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers.* European journal of applied physiology, 2010. **109**(3): p. 473-481.
71. Ainegren, M., et al., *Skiing economy and efficiency in recreational and elite cross-country skiers.* The Journal of Strength & Conditioning Research, 2013. **27**(5): p. 1239-1252.
72. Talsnes, R.K., et al., *Laboratory-and field-based performance-predictions in cross-country skiing and roller-skiing.* Plos one, 2021. **16**(8): p. e0256662.
73. Solli, G.S., E. Tønnessen, and Ø. Sandbakk, *The Training Characteristics of the World's Most Successful Female Cross-Country Skier.* Front Physiol, 2017. **8**: p. 1069.
74. Stöggl, T., S. Lindinger, and E. Müller, *Analysis of a simulated sprint competition in classical cross country skiing.* Scandinavian journal of medicine & science in sports, 2007. **17**(4): p. 362.
75. Sandbakk, Ø., G.S. Solli, and H.-C. Holmberg, *Sex differences in world-record performance: the influence of sport discipline and competition duration.* International journal of sports physiology and performance, 2018. **13**(1): p. 2-8.
76. Lindinger, S., et al., *Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing.* European Journal of Applied Physiology, 2009. **106**(3): p. 353-363.
77. Lindinger, S.J., et al., *Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing.* Eur J Appl Physiol, 2009. **106**(3): p. 353-63.
78. Calbet, J.A.L., et al., *Why do arms extract less oxygen than legs during exercise?* American Journal Of Physiology. Regulatory Integrative And Comparative Physiology, 2005. **289**(5): p. 1448-58.
79. Sandbakk, O., *Praktical Implementation of Strength Training to Improve the Performance of World-Class Cross-Country Skiers* Kinesiology (Zagreb, Croatia), 2018. **50**(S1): p. 155.

80. Østerås, S., et al., *Contribution of Upper-Body Strength, Body Composition, and Maximal Oxygen Uptake to Predict Double Poling Power and Overall Performance in Female Cross-Country Skiers.* J Strength Cond Res, 2016. **30**(9): p. 2557-2564.
81. Skattebo, Ø., et al., *Upper body heavy strength training does not affect performance in junior female cross‐country skiers.* Scandinavian journal of medicine & science in sports, 2016. **26**(9): p. 1007-1016.
82. Undebakke, V., et al., *Comparison of physiological and perceptual responses to upper-, lower-, and whole-body exercise in elite cross-country skiers.* The Journal of Strength & Conditioning Research, 2019. **33**(4): p. 1086-1094.
83. Børve, J., et al., *Upper-body muscular endurance training improves performance following 50 min of double poling in well-trained cross-country skiers.* Frontiers in physiology, 2017. **8**: p. 690.
84. Boushel, R., et al., *Low‐intensity training increases peak arm VO2 by enhancing both convective and diffusive O2 delivery.* Acta Physiol (Oxf), 2014. **211**(1): p. 122-134.

85. Stöggl, T., et al., *Automatic classification of the sub-techniques (gears) used in cross-country ski skating employing a mobile phone.* Sensors, 2014. **14**(11): p. 20589-20601.
86. Myklebust, H., T. Losnegard, and J. Hallen, *Differences in V1 and V2 ski skating techniques described by accelerometers.* Scand J Med Sci Sports, 2014. **24**(6): p. 882-93.
87. Losnegard, T., et al., *Kinematical analysis of the V2 ski skating technique: a longitudinal study.* Journal of Sports Sciences, 2017. **35**(12): p. 1219-1227.
88. Lindinger, S., T. Stöggl, and E. Mueller, *Biomechanical charateristics of further developed classical and skating techniques in cross-country skiing sprint competitions.* Journal of Biomechanics, 2006. **39**: p. S187-S187.
89. McKay, A.K.A., et al., *Defining Training and Performance Caliber: A Participant Classification Framework.* Int J Sports Physiol Perform, 2022. **17**(2): p. 317–331-15.
90. Foss, Ø. and J. Hallen, *Validity and stability of a computerized metabolic system with mixing chamber.* International journal of sports medicine, 2005. **26**(07): p. 569-575.
91. Montagut, Y., et al., *QCM technology in biosensors.* Biosensors-Emerging Materials and Applications, 2011: p. 153-178.
92. Borg, A.V.G., *Psychophysical bases of perceived exertion.* Medicine & Science in Sports & Exercise, 1982. **14**(5): p. 377-381.
93. Danielsen, J., et al., *Mechanical Energy and Propulsion in Ergometer Double Poling by Cross-country Skiers.* Med Sci Sports Exerc, 2015. **47**(12): p. 2586-94.
94. de Leva, P., *Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters.* J Biomech, 1996. **29**(9): p. 1223-30.
95. Hermens, H.J., et al., *Development of recommendations for SEMG sensors and sensor placement procedures.* J Electromyogr Kinesiol, 2000. **10**(5): p. 361-74.
96. van den Tillaar, R. and A. Saeterbakken, *Effect of fatigue upon performance and electromyographic activity in 6-RM bench press.* J Hum Kinet, 2014. **40**: p. 57-65.
97. Ball, N. and J. Scurr, *Electromyography normalization methods for high-velocity muscle actions: review and recommendations.* J Appl Biomech, 2013. **29**(5): p. 600-608.
98. Albertus-Kajee, Y., et al., *Alternative methods of normalising EMG during running.* J Electromyogr Kinesiol, 2011. **21**(4): p. 579-586.
99. Hegge, A.M., et al., *Gender differences in power production, energetic capacity and efficiency of elite cross-country skiers during whole-body, upper-body, and arm poling.* Eur J Appl Physiol, 2016. **116**(2): p. 291-300.
100. Vandbakk, K., et al., *Effects of upper-body sprint-interval training on strength and endurance capacities in female cross-country skiers.* PLoS One, 2017. **12**(2): p. e0172706.
101. Antonio, J., et al., *Comparison of Dual-Energy X-ray Absorptiometry (DXA) Versus a Multi-Frequency Bioelectrical Impedance (InBody 770) Device for Body Composition Assessment after a 4-Week Hypoenergetic Diet.* J Funct Morphol Kinesiol, 2019. **4**(2): p. 23-0.
102. Sandbakk, Ø., et al., *Analysis of Classical Time-Trial Performance and Technique-Specific Physiological Determinants in Elite Female Cross-Country Skiers.* Frontiers in Physiology, 2016. **7**: p. 326.

103. Holmberg, H.-C., et al., *Contribution of the legs to double-poling performance in elite cross-country skiers.* Medicine & science in sports & exercise, 2006. **38**(10): p. 1853-1860.
104. Smith, G., *Cross-country skiing: Technique, equipment and environmental factors affecting performance*, in *Biomechanics in sport. IOC Encyclopedia of Sports Medicine Series*, V. Zatsiorsky, Editor. 2000, Blackwell Science: Oxford. p. 247–270.
105. Cohen, J., *Statistical power analysis for the behavioral sciences*. 2nd ed. ed, ed. 2d. 1988., Hillsdale, N.J.: Lawrence Erlbaum.
106. Hopkins, W., et al., *Progressive statistics for studies in sports medicine and exercise science.* Medicine+ Science in Sports+ Exercise, 2009. **41**(1): p. 3.
107. Lakens, D., *Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs.* Front Psychol, 2013. **4**: p. 863.
108. Calkins, K.G., *Applied statistics: more correlation coefficients. Retrieved November 29, 2006,.* http://www.andrews.edu/˜calkins/math/edrm611/edrm13.htm, 2005.
109. Danielsen, J., et al., *The effect of exercise intensity on joint power and dynamics in ergometer double-poling performed by cross-country skiers.* Hum Mov Sci, 2018. **57**: p. 83-93.
110. Van Hall, G., et al., *Leg and arm lactate and substrate kinetics during exercise.* Am J Physiol Endocrinol Metab, 2003. **284**(1): p. E193-205.
111. Ørtenblad, N., et al., *The Muscle Fiber Profiles, Mitochondrial Content, and Enzyme Activities of the Exceptionally Well-Trained Arm and Leg Muscles of Elite Cross-Country Skiers.* Front Physiol, 2018. **9**(AUG): p. 1031-1031.
112. Calbet, J.A.L., et al., *Maximal muscular vascular conductances during whole body upright exercise in humans.* J Physiol, 2004. **558**(1): p. 319-331.
113. Berg, J., et al., *Comparison of mitochondrial respiration in M. triceps brachii and M. vastus lateralis between elite cross-country skiers and physically active controls.* Frontiers in physiology, 2019. **10**: p. 365.
114. Ettema, G. and H.W. Lorås, *Efficiency in cycling: a review.* Eur J Appl Physiol, 2009. **106**(1): p. 1-14.
115. Stöggl, L.T. and H.-C. Holmberg, *Force interaction and 3D pole movement in double poling.* Scandinavian Journal of Medicine & Science in Sports, 2011. **21**(6): p. e393-e404.
116. Lindinger, S.J., et al., *Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing.* Eur J Appl Physiol, 2009. **106**(3): p. 353-363.
117. Danielsen, J., et al., *Mechanical energetics and dynamics of uphill double-poling on roller-skis at different incline-speed combinations.* PloS ONE, 2019. **14**(2): p. e0212500.
118. Danielsen, J., et al., *Mechanical energy and propulsion mechanics in roller-skiing double-poling at increasing speeds.* PloS one, 2021. **16**(7): p. e0255202-e0255202.
119. Hill, A.V., *The heat of shortening and the dynamic constants of muscle.* Proceedings of the Royal Society of London. Series B - Biological Sciences, 1938. **126**(843): p. 136-195.
120. Stöggl, T.L. and E. Müller, *Kinematic determinants and physiological response of cross-country skiing at maximal speed.* Medicine and Science in Sports and Exercise, 2009. **41**(7): p. 1476-1487.

121. Zoppirolli, C., et al., *Changes in upper and lower body muscle involvement at increasing double poling velocities: an ecological study.* Scand J Med Sci Sports, 2017. **27**(11): p. 1292-1299.
122. Bojsen-Møller, J., et al., *Muscle use during double poling evaluated by positron emission tomography.* Journal of Applied Physiology, 2010. **109**(6): p. 1895-1903.
123. Zoppirolli, C., et al., *The effectiveness of stretch–shortening cycling in upper-limb extensor muscles during elite cross-country skiing with the double-poling technique.* J Electromyogr Kinesiol, 2013. **23**(6): p. 1512-1519.
124. Sandbakk, Ø., et al., *Analysis of a sprint ski race and associated laboratory determinants of world-class performance.* European Journal of Applied Physiology, 2011. **111**(6): p. 947-957.
125. Sandbakk, Ø. and H.-C. Holmberg, *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): p. 1003-1011.
126. Laursen, P.B., *Training for intense exercise performance: high-intensity or high-volume training?* Scand J Med Sci Sports, 2010. **20 Suppl 2**: p. 1-10.
127. Midgley, A.W., L.R. McNaughton, and A.M. Jones, *Training to Enhance the Physiological Determinants of Long-Distance Running Performance: Can Valid Recommendations be Given to Runners and Coaches Based on Current Scientific Knowledge?* Sports Med, 2007. **37**(10): p. 857-880.
128. Haugnes, P., et al., *The Interval-Based Physiological and Mechanical Demands of Cross-Country Ski Training.* Int J Sports Physiol Perform, 2019. **14**(10): p. 1-1377.
129. Stöggl, T.L., et al., *Pacing, Exercise Intensity, and Technique by Performance Level in Long-Distance Cross-Country Skiing.* Frontiers in Physiology, 2020. **11**(17).
130. Zoppirolli, C., et al., *Following a Long-Distance Classical Race the Whole-Body Kinematics of Double Poling by Elite Cross-Country Skiers Are Altered.* Front Physiol, 2018. **9**.
131. Coyle, E.F., *Physiological Regulation of Marathon Performance.* Sports Med, 2007. **37**(4-5): p. 306-311.
132. Faria, E.W., D.L. Parker, and I.E. Faria, *The Science of Cycling.* Sports Med, 2005. **35**(4): p. 285-312.
133. Sandbakk, Ø., *Praktical Implementation of Strength Training to Improve the Performance of World-Class Cross-Country Skiers.* Kinesiolgy, 2018. **50**: p. 1-8.
134. Street, G.M., *Biomechanics of cross-country skiing.* Winter sports medicine, 1990: p. 284-301.
135. Komi, P.V. and R.W. Norman, *Preloading of the thrust phase in cross-country skiing.* International Journal of Sports Medicine, 1987. **8**(1): p. 48-54.
136. Ekstrom, H., *Force interplay in cross-country skiing.* Scandinavian Journal of Sports Sciences, 1981. **3**(2): p. 69-76.
137. Stöggl, L.T., et al., *General strength and kinetics: fundamental to sprinting faster in cross country skiing?* Scandinavian Journal of Medicine & Science in Sports, 2011. **21**(6): p. 791-803.
138. Undebakke, V., et al., *Comparison of Physiological and Perceptual Responses to Upper-, Lower-, and Whole-Body Exercise in Elite Cross-Country Skiers.* Journal of Strength and Conditioning Research, 2019. **33**(4): p. 1897-1177.

139. Ørtenblad, N., et al., *The Muscle Fiber Profiles, Mitochondrial Content, and Enzyme Activities of the Exceptionally Well-Trained Arm and Leg Muscles of Elite Cross-Country Skiers.* Frontiers in Physiology, 2018. **9**(AUG).
140. Helge, J.W., *Arm and leg substrate utilization and muscle adaptation after prolonged low -intensity training.* Acta physiologica, 2010. **199**(4): p. 519-528.
141. Losnegard, T., et al., *The influence of pole length on performance, O 2 cost, and kinematics in double poling.* International Journal of Sports Physiology and Performance, 2017b. **12**(2): p. 211-217.
142. Wasser, J., *Die technik der weltbesten skilanglaufer.* Leistungsport, 1982. **13**(1): p. 27-35.
143. Zoppirolli, C., et al., *Energetics and biomechanics of double poling in regional and high-level cross-country skiers.* European journal of applied physiology, 2015. **115**(5): p. 969.
144. Stöggl, L.T. and H.-C. Holmberg, *Double-Poling Biomechanics of Elite Cross-country Skiers: Flat versus Uphill Terrain.* Medicine & Science in Sports & Exercise, 2016. **48**(8): p. 1580-1589.
145. Pellegrini, B., L. Bortolan, and F. Schena, *Poling force analysis in diagonal stride at different grades in cross country skiers.* Scandinavian journal of medicine & science in sports, 2011. **21**(4): p. 589.
146. Onasch, F., A. Killick, and W. Herzog, *Is There an Optimal Pole Length for Double Poling in Cross Country Skiing.* J Appl Biomec, 2017. **33**: p. 197-202.
147. Losnegard, T., et al., *The Influence of Pole Length on Performance, O2 Cost, and Kinematics in Double Poling.* Int J Sports Physiol Perform, 2017b. **12**(2): p. 211-217.
148. Carlsen, C., et al., *Pole lengths influence O_2-cost during souble poling in higly trained cross-country skiiers.* Eur J Appl Physiol, 2018. **118**: p. 271-281.
149. Myklebust, H., Losnegard, T. Hallén, J. , *Differences in V1 and V2 ski skating techniques described by accelerometer.* Scandinavian Journal of Medicine & Science in Sports., 2014. **24**(6): p. 882-893.
150. Holmberg, H.C., et al., *Biomechanical analysis of double poling in elite cross-country skiers.* Med Sci Sports Exerc, 2005. **37**(5): p. 807-18.
151. Stoggl, T.L. and H.C. Holmberg, *Double-Poling Biomechanics of Elite Cross-country Skiers: Flat versus Uphill Terrain.* Med Sci Sports Exerc, 2016. **48**(8): p. 1580-9.
152. Sandbakk, O., et al., *The Physiological Capacity of the World's Highest Ranked Female Cross-country Skiers.* Med Sci Sports Exerc, 2016. **48**(6): p. 1091-100.
153. Stöggl, T. and B. Sperlich, *Polarized training has greater impact on the key endurance variables than threshold, high intensity, or high volum training.* Frontiers in Physiology, 2014. **5**(33): p. 1-9.
154. Stöggl, L.T. and L.H.-C. Holmberg, *Double-Poling Biomechanics of Elite Cross-country Skiers: Flat versus Uphill Terrain.* Med Sci Sports Exerc, 2016. **48**(8): p. 1580-1589.
155. Sylta, Ø., E. Tønnessen, and S. Seiler, *Do elite endurance athletes report their training accurately?* Int J Sports Physiol Perform, 2014. **9**(1): p. 85-92.
156. Seeberg, T., et al., *A multi-sensor system for automatic analysis of classical cross-country skiing techniques.* Sports Engineering, 2017. **20**(4): p. 313-327.
157. Bjerke, H., *Technician SWIX, Lillehammer.*, P.-Ø. Torvik, Editor. 2020.

Study I

A Comparison of Double Poling Physiology and Kinematics between Long-Distance and All-Round Cross-Country Skiers

Per-Øyvind Torvik[1], Øyvind Sandbakk[2], Roland van den Tillaar[1], Rune Talsnes[1], Jørgen Danielsen[2*]

[1]Nord University, Norway, [2]Norwegian University of Science and Technology, Norway

Submitted to Journal:
Frontiers in Sports and Active Living

Specialty Section:
Elite Sports and Performance Enhancement

Article type:
Original Research Article

Manuscript ID:
849731

Received on:
06 Jan 2022

Revised on:
14 Mar 2022

Journal website link:
www.frontiersin.org

Conflict of interest statement

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 contribution statement

Authors PØT, ØS, RvdT and JD planned and designed the study. Authors PØT, RvdT and JD performed the data collection. Authors PØT, ØS, RvdT, RT and JD analyzed and presented the data, authored, and finalized the manuscript for publication. Authors PØT, ØS, RvdT, RT and JD have approved the final manuscript.

Keywords

Electromyography, gross efficiency, kinematics, maximal oxygen uptake, XC skiing

Abstract

Word count: 316

Purpose: To compare physiological and kinematic responses to double poling (DP) between long-distance (LDS) and all-round (ARS) cross-country skiers. Methods: Five world-class LDS (28.8±5.1 yrs, maximal oxygen uptake (VO2max): 70.4±2.9 ml·kg-1·min-1) and seven ARS (22.3±2.8 yrs, VO2max: 69.1±4.2 ml·kg-1·min-1), both groups having similar training volumes and VO2max performed three identical tests; 1) submaximal and incremental tests to exhaustion while treadmill DP to determine gross efficiency (GE), peak oxygen uptake (DP-VO2peak) and peak speed; 2) submaximal and incremental running tests to exhaustion to determine GE, VO2max (RUN-VO2max) and peak speed; and 3) an upper-body pull-down exercise to determine one repetition maximum (1RM) and peak power. Physiological responses were determined during both DP and running, together with assessments of kinematic responses and electromyography (EMG) of selected muscles during DP. Results: Compared to ARS, LDS reached higher peak speed (22.1±1.0 versus 20.7±0.9 km·h-1, p=0.030), DP-VO2peak (68.3±2.1 versus 65.1±2.7 ml·kg-1·min-1, p=0.050) and DP-VO2peak/RUN-VO2max ratio (97% versus 94%, p=0.075) during incremental DP to exhaustion, as well as higher GE (17.2% versus 15.9%, p=0.029) during submaximal DP. There were no significant differences in cycle length or cycle rate between the groups during submaximal DP, although LDS displayed longer relative poling times (~2.4%-points) at most speeds compared to ARS (p=0.015). However, group x speed interaction effects (p<0.05) were found for pole angle and vertical fluctuation of body center of mass, with LDS maintaining a more upright body position and more vertical pole angles at touchdown and lift-off at faster speeds. ARS displayed slightly higher normalized EMG amplitude than LDS in the muscles rectus abdominis (p=0.074) and biceps femoris (p=0.027). LDS performed slightly better on 1RM upper-body strength (122 versus 114 kg, p=0.198), with no group differences in power in the pull-down exercise. Conclusions: The combination of better DP-specific aerobic energy delivery capacity, efficiency and technical solutions seem to contribute to the superior DP performance found among specialized LDS skiers in comparison to ARS.

Contribution to the field

Previous literature suggest that elite long-distance skiers outperform elite all-round skiers in double poling (DP) mainly due to lower oxygen cost/higher efficiency, without minimal or no differences in technique. In this study, this was examined further, with more kinematic data collected at a larger range of speeds during an incremental test to exhaustion than in previous studies. This paper furthers our understanding of long-distance cross-country skiing n which high-ranked skiers utilize mainly the double poling (DP) skiing technique. Not much is known regarding the physiological and technical adaptations occurring when elite skiers choose to perform such large amounts of training utilizing mainly DP, with minimal focus on all the other sub-techniques that all-round skiers must focus on as well. The data of this study indicate that technique or kinematics indeed seem to separate long-distance from all-round skiers in DP performance in addition to technique-specific physiological response. As such, our data indicate the potential for human adaptation to movement-specific stimuli.

Funding statement

NeXt Move was funded by the Faculty of Medicine at NTNU and Central Norway Regional Health Authority. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The laboratory facilities and equipment were provided by NeXt Move, Norwegian University of Science and Technology (NTNU).

Ethics statements

Studies involving animal subjects

Generated Statement: No animal studies are presented in this manuscript.

Studies involving human subjects

Generated Statement: Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Inclusion of identifiable human data

Generated Statement: No potentially identifiable human images or data is presented in this study.

Data availability statement

Generated Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

A Comparison of Double Poling Physiology and Kinematics between Long-Distance and All-Round Cross-Country Skiers

Per-Øyvind Torvik[1], Øyvind Sandbakk[2], Roland van den Tillaar[1], Rune Kjøsen Talsnes[1,3] and Jørgen Danielsen[2*]

[1]Department of Sports Science and Physical Education, Nord University, Meråker, Norway
[2]Centre for Elite Sports Research, Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology, Trondheim, Norway
[3]Meråker High School, Trøndelag County Council, Steinkjer, Norway

**Correspondence*
Jørgen Danielsen
jorgen.danielsen@ntnu.no

Running head

DP physiology and kinematics of long-distance and all-round XC skiers

Abstract word counting: 313

Text-Only Word Count: 5208

Number of Figures and Tables: 5 Figures and 3 Tables

Abstract

Purpose: To compare physiological and kinematic responses to double poling (DP) between long-distance (LDS) and all-round (ARS) cross-country skiers. **Methods**: Five world-class LDS (28.8±5.1 yrs, maximal oxygen uptake (VO_{2max}): 70.4±2.9 $ml\cdot kg^{-1}\cdot min^{-1}$) and seven ARS (22.3±2.8 yrs, VO_{2max}: 69.1±4.2 $ml\cdot kg^{-1}\cdot min^{-1}$) athletes having similar training volumes and VO_{2max} performed three identical tests; 1) submaximal and incremental tests to exhaustion while treadmill DP to determine gross efficiency (GE), peak oxygen uptake (DP-VO_{2peak}) and peak speed; 2) submaximal and incremental running tests to exhaustion to determine GE, VO_{2max} (RUN-VO_{2max}) and peak speed; and 3) an upper-body pull-down exercise to determine one repetition maximum (1RM) and peak power. Physiological responses were determined during both DP and running, together with assessments of kinematic responses and electromyography (EMG) of selected muscles during DP. **Results:** Compared to ARS, LDS reached higher peak speed (22.1±1.0 versus 20.7±0.9 $km\cdot h^{-1}$, p=0.030), DP-VO_{2peak} (68.3±2.1 versus 65.1±2.7 $ml\cdot kg^{-1}\cdot min^{-1}$, p=0.050) and DP-$VO_{2peak}$/RUN-$VO_{2max}$ ratio (97% versus 94%, p=0.075) during incremental DP to exhaustion, as well as higher GE (17.2% versus 15.9%, p=0.029) during submaximal DP. There were no significant differences in cycle length or cycle rate between the groups during submaximal DP, although LDS displayed longer relative poling times (~2.4%-points) at most speeds compared to ARS (p=0.015). However, group x speed interaction effects (p<0.05) were found for pole angle and vertical fluctuation of body center of mass, with LDS maintaining a more upright body position and more vertical pole angles at touchdown and lift-off at faster speeds. ARS displayed slightly higher normalized EMG amplitude than LDS in the muscles rectus abdominis (p=0.074) and biceps femoris (p=0.027). LDS performed slightly better on 1RM upper-body strength (122 versus 114 kg, p=0.198), with no group differences in power in the pull-down exercise. **Conclusions:** The combination of better DP-specific aerobic energy delivery capacity, efficiency and technical solutions seem to contribute to the superior DP performance found among specialized LDS in comparison to ARS.

Keywords: electromyography; gross efficiency; kinematics; maximal oxygen uptake; XC skiing

Introduction

Competitive cross-country (XC) skiing consists of the Olympic disciplines, with competition formats ranging from short sprint competitions (~1.3-1.8 km) to 30- and 50-km races performed in undulating terrain, and long-distance XC skiing (Ski Classics) consisting of distances ranging from 40 to 90 km performed in flatter terrain using the classical style. All-round skiers (ARS) competing in the Olympic disciplines are known for their high maximal oxygen uptake (VO_{2max}), as well as high technique-specific peak oxygen uptakes (VO_{2peak}) and gross efficiency (GE) in the main sub-techniques of the classical and skating styles (1-4). While the Olympic XC skiing disciplines include the use of, and constant changes between, many different sub-techniques (1, 5, 6), the flatter course profiles in long-distance XC skiing events have led to extensive and, at the elite level, almost exclusive use of the double poling (DP) sub-technique (7-10).

In order to adapt to these competitive demands, specialized long-distance XC skiers (LDS) perform a higher percentage of their total training volume using DP than ARS (~50% versus ~25%) (11). Due to the higher volumes of DP training among LDS, superior technique-specific physiological adaptations and greater upper-body strength and power may be expected in comparison to typical ARS. In this context, Skattebo et al. (7) found lower oxygen cost and better GE during submaximal DP in LDS compared to ARS. In the same study, LDS achieved similar DP performance in the laboratory (peak speed and time to exhaustion) as the ARS despite obtaining lower VO_{2peak} values in both DP and running, as well as lower performance during a time to exhaustion test in running (7).

The higher proportion of the annual training volume performed exclusively in DP by LDS targeting the upper-body adaptations may also positively influence DP speed and efficiency by improving technical solutions (12) and delaying fatigue in long-distance DP races (13). However, Skattebo et al. (7) found no kinematic differences that could possibly explain the observed differences in submaximal oxygen cost during submaximal DP between LDS and ARS. Contrary, Zoppirolli et al. (14) have previously shown that the best LDS are able to maintain speed and cycle length better than their lower-performing counterparts in the long-distance race Marcialonga, although the technical solutions in DP among specialized LDS are currently understudied. Accordingly, detailed examination of the underlying mechanisms related to engagement of different body segments and EMG amplitude of muscles in DP should be explored in LDS and compared to the patterns obtained from ARS.

The technical solutions associated with DP performance in ARS include a distinct extended hip, knee and ankle (the “high hip, high heel” strategy), with a clear forward lean of the body during the poling phase (15-17). This high initial position followed by rapid downward-forward body movement during propulsion through trunk, hip, knee, and ankle flexion increases the ability to rapidly generate pole force during a short and dynamic poling phase. Furthermore, Holmberg et al. (15) and Stöggl and Holmberg (18) emphasized the importance of a more vertical pole plant during DP in relatively flat terrain. A more vertical pole plant, apart from increasing pole contact time, is considered important for muscle pre-activation (and time to build up force) and flexion-extension elbow (and shoulder) angle patterns (15, 16, 19). Based on EMG, Holmberg et al. (15) found proximo-distal sequential muscle activation patterns in the upper body during DP, with EMG amplitude of rectus femoris and rectus abdominis preceding that of latissimus dorsi and triceps brachii However, it is not known whether such characteristics may differ between ARS and LDS, which could indicate differences in movement timing and kinematic. Furthermore, Zoppirolli et al. (20) found that elite skiers had a more advantageous movement of center of body mass (CoM) in DP than lower-ranked skiers, with less downward and more forward CoM movement in the poling phase. Whether skiers specialized in DP have further developed such technical solutions or use them differently than less DP specialized ARS remains to be elucidated.

Therefore, the aim of this study was to compare physiological and kinematic responses to DP, as well as upper-body strength and power between LDS and ARS. Methodologically, the groups were matched for VO_{2max} in running and overall training volume. Since LDS perform more of their total training volume using DP, it was hypothesized that specialized LDS would achieve better DP performance, and higher VO_{2peak} and GE in DP than ARS, and that these differences would coincide with better technical solutions among LDS.

Methods

Participants

Twelve Norwegian male, competitive XC skiers, including five world-class LDS competing primarily in Ski Classics and seven ARS competing in all-round skiing volunteered to participate in this study. Both groups displayed approximately equal characteristics in terms of overall training volume and overall aerobic capacity as measured by VO_{2max} in running (RUN-VO_{2max}). The participants' ages, anthropometrics, physiological characteristics, and training volumes are presented in **Table 1**.

Prior to the data collection, all participants were informed about the content of the study before giving their written consent to participate. The study was approved by the Norwegian Centre for Research Data and carried out in line with current ethical standards for human participation in scientific research of the Declaration of Helsinki.

****Table 1** around here**

Procedures

The skiers performed three tests on separate days in a randomized order: day 1) treadmill running tests, day 2) treadmill DP tests, day 3) body-mass scan and an upper-body pull-down exercise to determine one repetition maximum (1RM) strength and power. Performance and physiological responses were determined during both treadmill running and DP, while three-dimensional kinematics and EMG of selected muscles were obtained during DP. Before each test, the participants arrived at the laboratory in a rested and well-hydrated state, at least two hours postprandial and without having consumed alcohol or caffeine and performed any strenuous exercise 24 h before the tests.

Double poling tests

All DP tests were performed at a treadmill inline of 5%, simulating moderate uphill terrain in long-distance races. Initially, the participants performed a 10-min warm-up at 10 $km \cdot h^{-1}$ (~60-70% of maximal heart rate [HR_{max}]). Before the start of the test, reflective markers and EMG electrodes were attached to the participant's body. Thereafter, one 5-min submaximal workload was performed at 12.5 $km \cdot h^{-1}$ in which steady-state metabolic rates were achieved. After a 2-min break, an incremental test to exhaustion was performed to determine VO_{2peak} in DP (DP-VO_{2peak}) and performance measured as peak speed (DP-V_{peak}). The test started at 15 $km \cdot h^{-1}$ with increasing speed by 1.5 $km \cdot h^{-1}$ every minute until voluntary exhaustion. Termination was defined as when the skiers could no longer keep up and their roller-ski wheels crossed a mark in the middle of the treadmill. Performance (DP-V_{peak}) was defined as: $V_{peak} = V_c + ((t_{final}/60)*\Delta V)$ with V_c the speed of the last completed workload, t_{final} the duration of the last workload, and ΔV the change in speed between each workload. DP-VO_{2peak} was defined as the average of the two highest consecutive VO_2 measurements averaged over 30-sec periods, and peak heart rate (HR_{peak}) as the highest heart rate during a 5 sec period.

Running tests

All running tests were performed at a treadmill incline of 10.5%. First, the participants performed a 10-min warm-up at 8 km·h^{-1} (~60-70% of HR$_{max}$), followed by one submaximal 5-min workload at 10 km·h^{-1}, where steady-state metabolic rates were achieved. Thereafter, the participants performed an incremental test to exhaustion to determine RUN-VO$_{2max}$ and performance measured as V$_{peak}$ (RUN-V$_{peak}$). The test started at 10 km·h^{-1} with the speed subsequently increased by 1 km·h^{-1} every minute until voluntary exhaustion. RUN-VO$_{2max}$, RUN-V$_{peak}$ and HR$_{max}$ were calculated in the same way as in the abovementioned DP test. We chose to perform a running test rather than a more ski-specific test with diagonal stride on roller skis, mainly because our LDS had performed very limited training using diagonal stride over the last years, which is a typical trend in the training routines of modern LDS. In contrast, they typically perform extensive amounts of running (especially high-intensity sessions), similar to the training of ARS (7).

Upper-body strength and power

After a 10-min running warm-up (~60-70% of HR$_{max}$),1RM strength and power were determined in a pull-down exercise simulating the DP movement emphasizing elbow extension, shoulder extension, and trunk flexion movements (21, 22). Sitting position was adjusted at the cable pull-down apparatus to approximately 90° angles in the knee and ankle joints and a stable back at a ~120° angle to the seat. The skiers were strapped around the hip to the seat to isolate muscle work mainly in the upper body, excluding most of the possibility to use the lower body. Before their maximal effort in 1RM strength, the skiers performed ten repetitions at 60%, eight repetitions at 70%, six repetitions at 80% and three repetitions at 90% of their estimated 1RM based on familiarization with the same exercise. Thereafter, 1RM was determined by increasing the load by 1.25–2.5 kg per attempt until 1RM was achieved, and the participants failed to perform the exercise correctly. There was a 2 min break between each 1RM attempt. The 1RM results were further converted to mean power by multiplying mass with mean velocity of the pull-down movement, as previously described (23). Mean velocity was measured with a linear encoder at 200Hz (Muscle Lab Power, Ergotest Innovation AS, Porsgrunn, Norway), and data was processed with the associated computer software program (MuscleLab 3010E, software version 7.17; Ergotest Technology AS).

Anthropometrics/body composition

All participants were assessed for body composition immediately upon their arrival at the lab on the morning of test day 3 by using the InBody 770 device (InBody 770, Cerriots, CA, USA). During the test, the participants wore only underpants, while all metal, watches, and jewelry were removed, and they stood barefoot on the electrodes in the platform. The participants held their thumb and fingers in direct contact with the electrodes on the handles. They stood with their elbows extended and their shoulder joint abducted at a 30-degree angle for approximately 60 seconds while body composition was determined. This included body mass, fat-free mass, and the distribution of total body mass in the trunk, legs, and arms. When comparing actual fat-free mass and fat mass, previous studies have shown that the InBody 770 is a valid alternative to dual energy X-ray absorptiometry (DEXA) in trained men and women (24), but the device slightly overestimates fat-free mass and underestimates fat mass by approximately 1-4.5% (25), depending on age, sex, training state, food intake and time of testing.

Measurements and analysis

Running and DP tests

The running and DP tests were performed on a 5×3 m motor-driven treadmill (Forcelink Technology, Zwolle, The Netherlands). All participants used the same pair of classic roller skis with standard wheels of resistance category 2 (IDT Sports, Lena, Norway). They used their own poles with special carbide tips to ensure optimal grip on the treadmill. During the incremental DP test, the participants were secured with a safety harness connected to the emergency brake of the treadmill. A towing test was performed to determine the coefficient of rolling resistance (μ) of the roller skis before and after all tests. The mean value of μ was 0.018 ± 0.001.

Respiratory variables

Respiratory variables were measured using open-circuit indirect calorimetry with a mixing chamber and 30 sec averaging of the variables measured (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany). The instruments were calibrated against ambient air conditions and certified gases of known concentrations of O_2 (15.0 ± 0.04%) and CO_2 (5.0 ± 0.01%) before each test session. The flow transducer (Triple V, Erick Jaeger GmbH, Hoechberg, Germany) was calibrated using a 3-L high-precision calibration syringe (Hans Rudoph Inc., Kansas City, MO, USA). Heart rate was measured with a Polar heart rate monitor (V800, Polar, Finland), whereas blood lactate concentrations were obtained from 20 µL of fingertip blood analyzed using the stationary Biosen C-Line lactate device (Biosen, EKF Industrial Electronics, Magdeburg, Germany). Rating of perceived exertion (RPE) was determined using the 6-20 Borg Scale (26).

Gross efficiency

GE during steady-state workloads in both running and DP were calculated by dividing work rate by metabolic rate (e.g., 27). Work rate was calculated as the rate of work done against gravity and rolling resistance: mgv(sin(α) + cos(a)μ), where m is body mass, g is acceleration of gravity (9.81), v is treadmill speed and α is the angle of the treadmill. Metabolic rate was obtained by converting the average VO_2 and RER of the final minute of the submaximal workloads and calculated according to Péronnet and Massicotte (28). In running, the rate of work done against rolling resistance is zero, and thus work rate was mgvsin(α).

Kinematics

A three-dimensional motion capture system (Qualisys, Gothenburg, Sweden) consisting of eight Oqus 400 cameras captured position data of reflective markers at a frequency of 250 Hz using Qualisys Track Manager. The 3D motion capture system was synchronized with the EMG recordings, using Musclelab 6000 (Ergotest Technology AS, Langesund, Norway). For both kinematics and EMG, at least ten full movement cycles at the workload of each participant were obtained and used for further analysis. Reflective markers were placed on the right side of the body on the following anatomical landmarks: styloid process of ulna, lateral epicondyle of humerus, lateral end of acromion process, greater trochanter, lateral epicondyle of femur, lateral malleolus (on the ski boot), head of fifth metatarsal (on the ski boot) (29). These markers defined six body segments: foot, shank, thigh, trunk (including head), arm, and forearm. One marker was placed 10 cm below the right pole grip and one marker was placed at the bottom of the right pole tip. Raw position data were low-pass filtered (fourth-order Butterworth) at 15 Hz. Segment position data was used to calculate body center of mass using de Leva (30) segmental inertial properties. Joint angles (elbow, shoulder, hip, knee, and ankle) and pole angle were calculated as described in Danielsen et al. (31). Time between pole on and off defined the poling phase, consecutive pole plants defined one movement cycle, while the time between pole off and on defined the swing phase. The instants of pole on and off were defined by using the (peak) second derivative of pole tip marker position data. Kinematics were analyzed in MATLAB (R2019b, Mathworks Inc., Natick, MA, USA).

Electromyography

EMG was measured according to the recommendations of the SENIAM (32), using Musclelab system v.10.5.60 (Ergotest AS, Porsgrunn, Norway). EMG was measured in nine muscles: triceps brachii, erector spinae at L4-L5, rectus abdominis, latissimus dorsi, gluteus maximus, biceps brachii, rectus femoris, gastrocnemius, tibialis anterior and biceps femoris. The skin was prepared by shaving, abrading, and cleaning with isopropyl alcohol to reduce skin impedance before positioning the electrodes over each muscle. To strengthen the signal, a conductive gel was applied to self-adhesive electrodes (Dri-Stick Silver circular sEMG Electrodes AE-131, NeuroDyne Medical, Cambridge, MA, USA). The electrodes (11 mm contact diameter, 20 mm center-to-center distance) were placed on the participant´s right side. To minimize noise from external sources, the EMG raw signal was amplified and filtered using a preamplifier located as near to the pickup point as possible. The common-mode rejection ratio was 106 dB, and the input impedance between each electrode pair was $>10^{12}\ \Omega$. The EMG signals were sampled at a rate of 1000 Hz. Signals were band-pass filtered (fourth-order Butterworth filter) with cut-off frequencies of 20 Hz and 500 Hz, and converted to root-mean-square signals using a hardware circuit network to create the linear envelope of the EMG signal (frequency response 450 kHz, averaging constant 12 ms, total error ± 0.5%) (33).

All kinematics and EMG data were time normalized for each participant and cycle and averaged over ~10 cycles for each speed. For each muscle, the peak EMG and the timing (occurrence of peak EMG in relation to normalized cycle time) at each speed were calculated. Cycle average normalized EMG (nEMG_{avg}) at all speeds was computed by normalizing cycle average EMG of each sub-maximal speed to peak EMG measured at V_{peak}, as recommended for high-velocity dynamic movements such as sprint running (34, 35) and high-speed DP.

Statistical analysis

All results are presented as mean ± standard deviations unless otherwise specified, and statistics were analyzed using SPSS version 27.0 (IBM Corp., Armonk, New York, USA) and Microsoft Excel 2017. Because all participants did not complete all speeds, most statistical analysis of kinematics and EMG was restricted to speeds between 12.5 and 21.0 $\text{km}\cdot\text{h}^{-1}$. Statistical analysis was performed using linear mixed models (LMM, with restricted maximum likelihood estimation), using the mixed command in SPSS, with participant-specific intercepts. To compare $_{\text{n}}\text{EMG}_{\text{avg}}$ and timing of peak EMG between groups, a LMM was applied with group (LDS, ARS) and speed (12.5 – 21.0 $\text{km}\cdot\text{h}^{-1}$) as fixed factors. To compare the timing of peak EMG between the nine muscles, an LMM was applied with group and muscle (nine muscles) as fixed factors. A LMM was used to compare the effects of group and speed (12.5–21.0 km·h^{-1}), as well as their interaction effects, on kinematics. Between-group comparisons of variables at submaximal and peak workloads, as well as possible differences in strength, power, and body composition, were compared using independent Welch's t-tests (36). Despite small number of participants, variables were approximately normally distributed in each group (variables and residuals assessed by normal QQ-plots). Effect sizes for local differences were calculated as Hedges' g_s (g_s) (37), where 0.2-0.5 constitutes a small effect, 0.5-0.8 a medium effect, and >0.8 a large effect (38).

Results

Body composition and 1RM upper-body strength

Table 2 shows body-composition measures and upper-body strength and power for both LDS and ARS. The LDS were heavier than ARS, and LDS also had more muscle mass located in the upper body and arms but a lower percentage of muscle mass in the legs. The LDS tended to display higher 1RM in the pull-down exercise than ARS, with no difference in mean power found between the two groups.

****Table 2** around here**

Performance and physiological responses

The LDS achieved higher DP-V_{peak} than ARS, although no difference in RUN-V_{peak} was found between groups (**Table 3**). Absolute values in RUN-VO_{2max} were higher in LDS than in ARS, although no between-group differences were found for body-mass normalized RUN-VO_{2max} (**Table 3**). Both absolute and body-mass normalized DP-VO_{2peak} were higher for the LDS compared to the ARS. Thus, the DP-VO_{2peak} to RUN-VO_{2max} ratio was higher in the LDS than in ARS (97% versus 94%, p=0.075, g_s=1.08). A similar pattern was found for HR_{peak}, with the LDS reaching 98% of their RUN-HR_{max} in DP compared to 95% in ARS (p=0.154, g_s=0.83). During submaximal DP, LDS displayed lower oxygen cost and higher GE than ARS (**Table 3**), with similar patterns observed for submaximal running, although the group differences in running were smaller.

****Table 3** around here**

Kinematics

There were no between-group differences in cycle length or cycle rate at any speed (**Fig 1**), with no differences in peak values for rate (1.12±0.18 Hz versus 1.04±0.08 Hz, p=0.385, g_s=0.58) or length (6.0±0.7 m versus 5.7±0.6 m, p=0.503, g_s=0.39) . The LDS had slightly longer poling times (p=0.193) than ARS, while relative poling times differed (p=0.015) at speeds between 12.5 and 18.0 km·h^{-1} (40-34% versus 37-31% in LDS and ARS, respectively). Significant interaction effects were found for pole angle at touchdown and lift-off (more vertical for LDS), and for the distance between pole tip and feet at touchdown (longer distance for LDS), and the LDS seemed better able to maintain these characteristics at higher speeds (**Fig 1**).

****Fig 1** around here**

Although joint angles appeared to be very similar in both groups (**Fig 2**), interaction effects were found for knee and hip angles at touchdown and for minimum hip angle during the poling phase, with the LDS maintaining a slightly more extended hip positioning at faster speeds (**Fig 2**). These differences led to the significant interaction and minor group effects on the minimum center of mass height.

****Fig 2** around here**

EMG

DP speed affected nEMG$_{avg}$ of most muscles (p<0.001, **Fig 3**) but less so for triceps brachii (p=0.202), erector spinae (p=0.177) and rectus femoris (p=0.620). nEMG$_{avg}$ showed a particular increase at speeds above 18 km·h^{-1}. No clear group versus speed interaction effects for any muscles were found (**Fig 3**). However, nEMG$_{avg}$ in rectus abdominis (p=0.074) and biceps femoris (p=0.027) were consistently slightly higher in the ARS than in the LDS (**Fig 3**). For some muscles, a large SD reflect somewhat lower or inconsistent EMG amplitudes between skiers.

****Fig 3** around here**

****Fig 4** around here**

Peak EMG amplitude occurred slightly earlier at faster speeds for triceps brachii, latissimus dorsi, and rectus abdominus ($p<0.01$), with no difference between groups for any muscle at any speed. When analyzing the timing of peak EMG amplitude for all muscles across all speeds, an effect of muscle was found ($p<0.001$), without any group ($p=0.520$) or interaction effects ($p=0.841$; **Fig. 4**).

Discussion

The aim of the present study was to compare physiological and kinematic responses to DP, as well as upper-body strength and power between LDS and ARS. The main findings were that LDS achieved better DP performance than ARS, which were coincided by higher DP-VO_{2peak}, DP-VO_{2peak}/RUN-VO_{2max} ratio and GE. In addition, our data indicated that LDS maintained more effective technical patterns at higher speeds, as indicated by the significant interaction effects for pole angle at touchdown and maximum knee and hip flexion angles during the poling phase, implying that LDS maintained a more upright body position with more vertically angled poles throughout the poling phase. Lastly, $nEMG_{avg}$ in rectus abdominus were higher in ARS than in LDS, with a similar pattern indicated for biceps femoris.

Physiological responses

As expected from their large amounts of DP-specific training (11), LDS reached higher DP-V_{peak} in comparison to ARS during the incremental test to exhaustion with no between-group differences observed in RUN-V_{peak}. Better DP performance in LDS were coincided by higher DP-VO_{2peak}, DP-VO_{2peak}/RUN-VO_{2max} ratios (i.e., 97% in LDS versus 94% in ARS), as well as with higher GE during submaximal DP. These findings differ partly from the study of Skattebo et al. (7), who found no difference between LDS and ARS in DP performance using a comparable design. These conflicting findings are most likely explained by different study groups, number of participants included, and the matching of LDS versus ARS. Skattebo et al. (7) matched the groups for overall performance level (elite ARS versus elite LDS), whereas the groups of the present study were matched for RUN-VO_{2max} and overall training volume. In Skattebo et al. (7), ARS achieved both higher RUN-VO_{2max} and DP-VO_{2peak} compared to LDS, although with similar DP-VO_{2peak}/RUN-VO_{2max} ratios observed between groups. Despite this, DP performance of LDS was identical to that of the ARS. Thus, independent of the different matching between groups, both the data of Skattebo et al. (7) and the present study therefore indicate that large amounts of DP-specific training leads to improved DP performance, beyond what may be expected based only on for example DP-VO_{2peak}.

The ability to reach high VO_{2peak} values is generally dependent on exercise modality, and the ability to generate high power within that particular modality. Therefore, the amount of muscle mass engaged in generating power is important (39). The fact that XC skiers can reach more than 90% of their RUN-VO_{2max} during DP further demonstrates that DP involves whole-body work (21, 31, 40, 41). The difficulty of reaching VO_{2max} in DP is likely to be related to longer diffusional distances, shorter mean transit times, and lower oxidative capacity in the upper than the lower body (41-43). Therefore, upper-body muscles are reported to extract ~10% lower O_2 than leg muscles (42) and contribute, together with a lower vascular conductance (44), to lower VO_{2peak} values in DP compared to running (45). Recently, Berg et al. (46) found higher mitochondrial respiration in the upper body but equal in the lower body when comparing XC skiers and physically active controls. It may be hypothesized that the average DP-VO_{2peak}/RUN-VO_{2max} ratio among LDS in the current study, which to our knowledge is the highest ever reported in the literature (47) is due to the high volumes of DP-specific training in LDS which may further increase O_2 extraction and/or enhance mitochondrial respiration in upper-body muscles beyond what has previously been shown. In support of this, we additionally found small differences between LDS and ARS in body composition, with the LDS having more muscle volume in the upper body and arms. Accordingly, the more DP-specific training among LDS may induce better aerobic energy delivery, allowing LDS to reach a higher DP-VO_{2peak} and thereby achieve higher DP performance.

The higher GE and lower oxygen cost in LDS than ARS during submaximal DP in the current study agrees in part with the findings of Skattebo et al. (7), who found lower oxygen cost in LDS than ARS, but smaller differences in GE (17.2% for ARS versus 17.9% for LDS at 252 W). This discrepancy in GE can partly be explained by the higher work rate of LDS compared to ARS in our data, due to their higher body mass because of the non-zero offset of the metabolic – work rate relationship (48, 49). Our findings on oxygen cost and GE during submaximal running further illustrate this point, with these values also being slightly better for LDS than ARS. However, the group differences are larger for DP than for running, demonstrating an effect beyond what can be explained by work rate. Also, although oxygen cost (values relative to body mass) suffers from the same problem with ratios, these values are more interpretable as body mass is transported against gravity in our protocol as well as during XC skiing races. The speculation above concerning higher mitochondrial respiration in the upper-body muscles of LDS compared to ARS, due to more DP-specific training over more years, may also be a possible explanation for the higher GE of LDS. In any case, despite more upper-body and arm muscle mass (and total mass) – forcing LDS to generate higher work rates at a given speed than ARS – LDS do so at equal or lower metabolic rates than ARS. Therefore, both our data and those of Skattebo et al. (7) on oxygen cost and GE during submaximal DP suggests that skiing efficiency/economy are coupled to DP performance. In short performance tests, but probably more so in long-distance races, efficiency and economy may be more performance determinant than maximal aerobic energy delivery (7) .

Kinematic responses

Due to the large amount of DP-specific training in LDS in Torvik et al. (11), we hypothesized that better GE and performance in DP among LDS would coincide with better technical solutions. However, we found no differences in cycle length or rate between groups, either at submaximal or at high speeds to support this hypothesis. These findings are in agreement with those of Skattebo et al. (7) , and can therefore not explain the observed differences in GE and oxygen cost between groups. Although most kinematic variables were similar between groups, LDS had a longer relative poling time at most speeds, while group versus speed interaction effects were found for pole angle (LDS more vertical poles), minimum height of the CoM within the poling phase (LDS less deep) and hip and knee angles, with all these differences previously linked to DP performance (18, 20). The interactions found in the present study therefore imply that the LDS were better able to maintain certain technical aspects as speed increased. Moreover, $nEMG_{avg}$ in rectus abdominus tended to be higher in ARS than in LDS, with a similar pattern indicated for biceps femoris. Thus, it seems that a range of small technique differences may help LDS to achieve higher $DP\text{-}V_{peak}$ and better GE compared to ARS.

At all speeds, the LDS displayed slightly longer relative poling times than the ARS, but with only a minimal differences in time allowed to generate force (+0.02 s for LDS, $p{\sim}0.200$, $g_s{\sim}0.7$), which could reduce the percentage of 1RM needed to perform the DP motion (19). Furthermore, more vertically planted poles have been described as part of a preferred strategy of elite skiers to achieve a more dynamic and explosive poling phase, in which body mass is used effectively to generate pole force (15, 19, 50, 51). As speed increased, we found that the LDS were able to maintain pole angle at touchdown at ~83°, while for ARS this angle decreased towards 79-80°.

The related distance between the pole tip and toe at touchdown increased from ~30 cm to ~48 cm from 12.5 to 19.5 km·h^{-1} in the LDS and they were able to maintain this distance up to V_{peak}, while the ARS increased this distance up to ~44 cm at 19.5 km·h^{-1} but then it dropped at V_{peak}. At higher speeds, the ability to place the poles in such advantageous positions seems to become important and may be a limitation for ARS because of the inverse relationship between muscle contraction velocity and force (16, 52).

DP technique in terms of joint angles also appeared very similar in both groups (Figs 2 and 3). However, group versus speed interaction effects were found for knee and hip angles at touchdown and for minimum hip angle during the poling phase, which led to the significant interaction and minor group effect on minimum CoM height (Fig 1). Although the high hip high heel DP strategy and thus considerable heightening and lowering of the CoM is a characteristic of the dynamics in modern DP (15, 51), it must be performed effectively so that the body mass (gravity) and active use of trunk flexion muscles (e.g., rectus abdominis) can be used to increase pole forces. At the same time, this strategy seems to require a certain amount of CoM lowering, and the finding that the LDS appeared to lower their CoM less than the ARS agrees with previous findings of (14) who found that the amount of CoM lowering was dependent on the skier's performance level. This might be related to keeping the amount of work required to heighten and reposition the body at a minimum (14, 51). Overall, these findings suggest that the LDS were able to maintain a slightly more upright body position throughout the cycle, which may explain their lower rectus abdominis $nEMG_{avg}$ at most speeds. If the skier is not able to maintain a rather upright body position throughout the cycle, whereby the poles are planted more vertically, a greater demand might be placed on trunk flexion muscles. However, these underlying mechanisms remain speculative and must be investigated further in future studies.

Overall, both EMG amplitude and timing of peak EMG amplitude was very similar between groups. Increasing speed led to a larger increase in $nEMG_{avg}$ in the core and lower extremities than in triceps brachii and latissimus dorsi, which agrees with previous findings of on-snow DP (53). The observed difference in rectus abdominis and biceps femoris $nEMG_{avg}$ between LDS and ARS, with LDS showing lower $nEMG_{avg}$, may further indicate that ARS work at a higher relative effort at submaximal speeds. This higher $nEMG_{avg}$ for ARS at submaximal DP speeds may, however, be entirely due to LDS reaching higher peak speeds, with a correlation between EMG amplitudes and DP speed for these muscles. Because of this, we also normalized the RMS EMG to 12.5 km/h. This removed the group differences completely also for rectus abdominis and biceps femoris, indicating that the observed differences were due to differences in V_{peak}. Given the kinematic group differences that appear while approaching V_{peak}, it can be speculated whether the lower peak EMG amplitude in ARS is explained by lower DP-V_{peak} or whether lower technical ability (including muscle coordination and neuromuscular muscle-power factors) contributes to the lower V_{peak}. These statements are not mutually exclusive, and this issue should be examined further. Combined, the kinematic, strength (as well as muscle mass distribution), and EMG data of the current study suggest that several factors contribute together to the observed group difference in DP-V_{peak}. Working at lower relative efforts (especially in terms of oxygen cost) at a given speed will certainly contribute to delaying fatigue during long-distance events. Here, it should also be noted that we found similar sequential EMG activation patterns throughout the DP cycle as previously described by Holmberg et al. (15), but no group differences related to timing of EMG amplitude were found in our data.

Conclusions

This present study found superior DP performance in specialized long-distance skiers compared to all-round skiers which coincided with higher gross efficiency and lower oxygen cost during submaximal DP combined with higher DP-VO_{2peak}, as well as the highest DP-VO_{2peak}/RUN-VO_{2max} ratios ever reported in the literature. Specialized long-distance XC skiers also demonstrated longer relative poling times and lower normalized EMG amplitude in rectus abdominis and biceps femoris, as well as more muscle mass located in the upper body which coincided with better 1RM upper-body strength performance. In addition, specialized long-distance skiers were able to better maintain technique (i.e., more upright body position and more vertical pole angles) at faster speeds than all-round skiers. Taken together, the combination of better DP-specific aerobic energy delivery capacity, efficiency and technical solutions seem to contribute to the superior DP performance found among specialized long-distance XC skiers in comparison to all-round skiers.

List of abbreviations

DP – Double poling

RUN – Running

DP-VO_{2peak} – Double-poling peak oxygen uptake

RUN-VO_{2max} – Running maximal oxygen uptake

LDS - Long-distance cross-country skiers

ARS - All-round cross-country skiers

XC – Cross-country

DP-VO_{2peak}/RUN-VO_{2max} – Ratio between double-poling peak oxygen uptake and running maximal oxygen uptake

EMG – Electromyography

$nEMG_{avg}$ - Cycle average normalized EMG amplitude

GE - Gross efficiency

Acknowledgements

The authors would like to thank all skiers for their participation, enthusiasm and cooperation in this study, and Espen Kveli for the help during data collection.

Conflict of interest statement

None of the authors have any conflicts of interest to declare.

Author contribution statement

Authors PØT, ØS, RvdT and JD planned and designed the study. Authors PØT, RvdT and JD performed the data collection. Authors PØT, ØS, RvdT, RT and JD analyzed and presented the data, authored, and finalized the manuscript for publication. Authors PØT, ØS, RvdT, RT and JD have approved the final manuscript.

Figure legends

Fig 1. Kinematic responses as a function of speed in long-distance (LDS, n=5) versus all-round (ARS, n=7) cross-country skiers performing treadmill double poling at 5% inclination. Int, interaction; Gr, group. * indicates $p<0.05$.

Fig 2. The mean group difference (long-distance minus all-round cross-country skiers) and 95% CI of joint angles at touch down (left panels), the minimum angle reached within the poling phase (maximum angle for the shoulder) (middle panels), and maximum angles reached within the swing phase (right panels) during treadmill double poling at 5% inclination. Int, interaction; Gr, group.

Fig 3. Average normalized EMG ($nEMG_{avg}$) in long-distance (LDS, n=5) versus all-round (ARS, n=7) cross-country skiers performing treadmill double poling at 5% inclination. Int, interaction; Gr, group. * indicates $p<0.05$.
→ indicates a significant increase in EMG amplitude between these velocities and all right of the sign ($p<0.05$)

Fig 4. Occurrence of peak EMG amplitude during the cycle (average across all speeds) for all round (ARS, n=7) and long distance (LDS, n=5) cross-country skiers performing treadmill double poling at 5% inclination. RA, Rectus abdominis; TRI, Triceps brachii; BB, Biceps brachii; LD, Latissimus dorsi; ESP, Erector spinae; RF, Rectus abdominis; BF, Biceps femoris; TA, Tibialis anterior; GAS, Gastrocnemius
→ indicates a significant different to the muscles to the right of the sign ($p<0.05$)

Tables

Table 1. Age, anthropometrics, physiological characteristics, and training volumes of five world-class long-distance skiers (LDS) and seven elite male all-round skiers (ARS). Presented as mean ± SD.

Variable	LDS (n=5)	ARS (n=7)	p, g_s
Age (yr)	28.8±5.1	22.3±2.8	0.010, 1.72
Body height (cm)	183.1±7.4	182.3±5.3	0.989, 0.01
Body mass (kg)	80.2±7.1	74.2±5.3	0.190, 0.83
BMI	23.9±1.5	22.0±0.7	0.156, 0.83
HR_{max} (beats·min^{-1})	191±9	194±9	0.434, 0.44
Annual training volume (hrs)	810±52	780±66	

LDS, long-distance skiers; ARS, all-round skiers; VO_{2max}, maximal oxygen uptake in running; HR_{max}, maximal heart rate in running. p-value for independent t-test between groups, g_s is Hedges

Table 2. Body composition and 1RM upper-body strength and power for all participants pooled, five world-class long-distance skiers (LDS) and seven elite male all-round skiers (ARS). Presented as mean±SD.

Variables	Pooled (n=12)	LDS (n=5)	ARS (n=7)	p, g_s
Body composition				
Total mass (kg)	76.7±4.5	80.2±7.1	74.2±5.3	0.190, 0.83
Muscle mass (kg)	40.2±3.7	41.8±4.3	39.1±2.7	0.259, 0.72
Body mass index	23.1±1,5	23.8±0.6	22.5±1.7	0.115, 0.83
Upper body (kg)	30.6 ±2.7	32.0±3.2	29.6±1.8	0.219, 0.83
Percentage of total mass (%)	39.9±1.7	39.9±0.9	40.0±2.0	0.919, 0.05
Arms (kg)	8.1±0.9	8.6 ±1.1	7.8 ±0.6	0.186, 0.89
Percentage of total mass (%)	10.6±0.6	10.7±0.5	10.5±0.7	0.469, 0.39
Legs (kg)	21.4±1.9	21.7±2.4	21.1±1,4	0.664, 0.27
Percentage of total mass (%)	27.9±1.2	27.1±0.9	28.5±1.0	0.037, 1.31
Upper-body strength				
1RM (kg)	117.7±9.4	121.5±6.5	113.9±12.2	0.198, 0.68
1RM / total mass (kg)	1.5±0.1	1.5±0.1	1.5±0.2	0.851, 0.10
Power (W)	748.4 ±101.0	763.6 ±67.6	733.1 ±134.3	0.618, 0.25
Power / total mass (W/kg)	9.7±1.3	9.9±0.8	9.5±1.8	0.776, 0.16

1RM, one repetition maximum. p-value for independent t-test between groups, g_s is Hedges

Table 3. Performance and physiological responses to submaximal and incremental double poling (at 5% incline) and running (at 10.5% incline) in five world-class long-distance skiers (LDS) and seven elite male all-round skiers (ARS). Presented as mean±SD. p-values and g_s are reported for group comparisons (independent t-tests).

Variables	**Double poling**			**Running**		
	LDS	**ARS**	**p, g_s**	**LDS**	**ARS**	**p, g_s**
Performance test						
V_{peak} ($km \cdot h^{-1}$)	22.1 ± 1.0	20.7 ± 0.9	0.040, 1.36	15.1 ± 1.0	14.6 ± 0.8	0.475, 0.42
Peak work rate (W)	336 ± 39	289 ± 33	0.060, 1.22	350 ± 39	320 ± 21	0.176, 0.93
$VO_{2max/peak}$ ($mL \cdot min^{-1} \cdot kg^{-1}$)	68.3 ± 2.1	65.1 ± 2.7	0.043, 1.20	70.5 ± 2.8	69.1 ± 4.2	0.524, 0.33
$VO_{2max/peak}$ ($L \cdot min^{-1}$)	5.5 ± 0.6	4.8 ± 0.3	0.083, 1.31	5.6 ± 0.5	5.1 ± 0.3	0.094, 1.19
RER (-)	1.10 ± 0.03	1.12 ± 0.06	0.467, 0.37	1.17 ± 0.02	1.15 ± 0.05	0.366, 0.45
$HR_{max/peak}$ (bpm)	187 ± 4	184 ± 10	0.466, 0.36	191 ± 4	194 ± 8	0.390, 0.44
Borg (6-20)	18.2 ± 1.3	19.0 ± 1.2	0.304, 0.61	19.6 ± 0.5	19.3 ± 0.5	0.335, 0.57
Submaximal test						
Speed ($km \cdot h^{-1}$)	12.5	12.5		10	10	
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	39.4 ± 1.2	42.2 ± 2.6	0.033, 1.21	52.8 ± 0.8	54.6 ± 2.2	0.090, 0.91
VO_2 ($L \cdot min^{-1}$)	3.15 ± 0.32	3.14 ± 0.30	0.960, 0.03	4.22 ± 0.42	4.06 ± 0.39	0.530, 0.39
RER (-)	0.88 ± 0.04	0.94 ± 0.04	0.029, 1.45	0.94 ± 0.02	0.94 ± 0.04	0.875, 0.08
Metabolic rate (W)	1074 ± 102	1087 ± 110	0.829, 0.12	1466 ± 170	1408 ± 106	0.524, 0.40
Work rate (W)	185 ± 19	172 ± 13	0.247, 0.74	217 ± 23	202 ± 15	0.247, 0.74
Gross efficiency (%)	17.2 ± 0.5	15.9 ± 1.1	0.019, 1.38	14.8 ± 0.2	14.3 ± 0.5	0.069, 1.00

VO_{2max}, maximal oxygen uptake; VO_{2peak}, peak oxygen uptake; RER, respiratory exchange ratio; HR_{max}, maximal heart rate; HR_{peak}, peak heart rate; VO_2, oxygen uptake. p-value for independent t-test between groups, g_s is Hedges

References

1. 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):1003-11. Epub 2017/01/18. doi: 10.1123/ijspp.2016-0749. PubMed PMID: 28095083.
2. Sandbakk Ø, Holmberg HC. A reappraisal of success factors for Olympic cross-country skiing. *Int J Sports Physiol Perform* (2014) 9(1):117-21. Epub 2013/10/04. doi: 10.1123/ijspp.2013-0373. PubMed PMID: 24088346.
3. Saltin B. The physiology of competetive c.c. skiing across a four decade perspective: with a note on training induced adaptations and role of training a medium altitude. In: Müller E, Kornexl E, Raschner C, editors. *Science and skiing*. Cambridge: Chapman & Hall (1997). p. 435-69.
4. Holmberg HC. The elite cross-country skier provides unique insights into human exercise physiology. *Scan J Med Sci Sports* (2015) 25(S4):100-9.
5. 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. Epub 2020/09/30. doi: 10.1371/journal.pone.0239862. PubMed PMID: 32991633; PubMed Central PMCID: PMCPMC7523995.
6. Strøm Solli G, Kocbach J, Seeberg TM, Tjønnas J, Rindal OMH, Haugnes P, 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. Epub 2018/11/16. doi: 10.1371/journal.pone.0207195. PubMed PMID: 30440017; PubMed Central PMCID: PMCPMC6237352.
7. Skattebo Ø, Losnegard T, Stadheim HK. Double-Poling Physiology and Kinematics of Elite Cross-Country Skiers: Specialized Long-Distance Versus All-Round Skiers. *Int J Sports Physiol Perform* (2019) 14(9):1190-9. Epub 2019/03/07. doi: 10.1123/ijspp.2018-0471. PubMed PMID: 30840518.
8. Sagelv EH, Engseth TP, Pedersen S, Pettersen SA, Mathisen G, Heitmann KA, et al. Physiological Comparisons of Elite Male Visma Ski Classics and National Level Cross-Country Skiers During Uphill Treadmill Roller Skiing. *Front Physiol* (2018) 9:1523. Epub 2018/12/07. doi: 10.3389/fphys.2018.01523. PubMed PMID: 30505276; PubMed Central PMCID: PMCPMC6250767.
9. Zoppirolli C, Bortolan L, Stella F, Boccia G, Holmberg HC, Schena F, et al. Following a Long-Distance Classical Race the Whole-Body Kinematics of Double Poling by Elite Cross-Country Skiers Are Altered. *Front Physiol* (2018) 9:978. Epub 2018/08/10. doi: 10.3389/fphys.2018.00978. PubMed PMID: 30090070; PubMed Central PMCID: PMCPMC6069450.
10. Stöggl T, Hertlein M, Brunauer R, Welde B, Andersson EP, Swaren M. Pacing, Exercise Intensity, and Technique by Performance Level in Long-Distance Cross-Country Skiing. *Front Physiol* (2020) 11:17. Epub 2020/03/03. doi: 10.3389/fphys.2020.00017. PubMed PMID: 32116742; PubMed Central PMCID: PMCPMC7033470.
11. Torvik PØ, Strøm Solli G, Sandbakk Ø. The Training Characteristics of World-Class Male Long-Distance Cross-Country Skiers. *Front Sports Act Living* (2021) 3(20):641389. Epub 2021/03/16. doi: 10.3389/fspor.2021.641389. PubMed PMID: 33718870; PubMed Central PMCID: PMCPMC7947281.
12. Stöggl T, Lindinger S, Muller E. Analysis of a simulated sprint competition in classical cross country skiing. *Scand J Med Sci Sports* (2007) 17(4):362-72. Epub 2006/08/17. doi: 10.1111/j.1600-0838.2006.00589.x. PubMed PMID: 16911588.
13. Sandbakk Ø. PRACTICAL IMPLEMENTATION OF STRENGTH TRAINING TO IMPROVE THE PERFORMANCE OF WORLD-CLASS CROSS-COUNTRY SKIERS. *Kinesiology (Zagreb, Croatia)* (2018) 50(S1):155.
14. Zoppirolli C, Bortolan L, Schena F, Pellegrini B. Double poling kinematic changes during the course of a long-distance race: effect of performance level. *J Sports Sci* (2020) 38(8):863-72. Epub 2020/03/07. doi: 10.1080/02640414.2020.1736246. PubMed PMID: 32138604; PubMed Central PMCID: PMC32138604.

15. Holmberg HC, Lindinger S, Stöggl T, Eitzlmair E, Muller E. Biomechanical analysis of double poling in elite cross-country skiers. *Med Sci Sports Exerc* (2005) 37(5):807-18. Epub 2005/05/05. doi: 10.1249/01.mss.0000162615.47763.c8. PubMed PMID: 15870635.

16. Lindinger SJ, Stöggl T, Muller E, Holmberg HC. Control of speed during the double poling technique performed by elite cross-country skiers. *Med Sci Sports Exerc* (2009) 41(1):210-20. Epub 2008/12/19. doi: 10.1249/MSS.0b013e318184f436. PubMed PMID: 19092686.

17. Danielsen J, Sandbakk Ø, Holmberg HC, Ettema G. Mechanical Energy and Propulsion in Ergometer Double Poling by Cross-country Skiers. *Med Sci Sports Exerc* (2015) 47(12):2586-94. Epub 2015/06/26. doi: 10.1249/MSS.0000000000000723. PubMed PMID: 26110695.

18. Stöggl T, Holmberg HC. Force interaction and 3D pole movement in double poling. *Scand J Med Sci Sports* (2011) 21(6):e393-404. Epub 2011/05/07. doi: 10.1111/j.1600-0838.2011.01324.x. PubMed PMID: 21545537.

19. Lindinger SJ, Holmberg HC, Muller E, Rapp W. Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing. *Eur J Appl Physiol* (2009) 106(3):353-63. Epub 2009/03/13. doi: 10.1007/s00421-009-1018-5. PubMed PMID: 19280214.

20. Zoppirolli C, Pellegrini B, Bortolan L, Schena F. Energetics and biomechanics of double poling in regional and high-level cross-country skiers. *Eur J Appl Physiol* (2015) 115(5):969-79. Epub 2014/12/18. doi: 10.1007/s00421-014-3078-4. PubMed PMID: 25515019.

21. Hegge AM, Bucher E, Ettema G, Faude O, Holmberg HC, Sandbakk Ø. Gender differences in power production, energetic capacity and efficiency of elite cross-country skiers during whole-body, upper-body, and arm poling. *Eur J Appl Physiol* (2016) 116(2):291-300.

22. Østerås S, Welde B, Danielsen J, van den Tillaar R, Ettema G, Sandbakk Ø. Contribution of Upper-Body Strength, Body Composition, and Maximal Oxygen Uptake to Predict Double Poling Power and Overall Performance in Female Cross-Country Skiers. *J Strength Cond Res* (2016) 30(9):2557-64. Epub 2016/01/29. doi: 10.1519/JSC.0000000000001345. PubMed PMID: 26817743.

23. Vandbakk K, Welde B, Kruken AH, Baumgart J, Ettema G, Karlsen T, et al. Effects of upper-body sprint-interval training on strength and endurance capacities in female cross-country skiers. *PLoS One* (2017) 12(2):e0172706.

24. Antonio J, Kenyon M, Ellerbroek A, Carson C, Burgess V, Tyler-Palmer D, et al. Comparison of Dual-Energy X-ray Absorptiometry (DXA) Versus a Multi-Frequency Bioelectrical Impedance (InBody 770) Device for Body Composition Assessment after a 4-Week Hypoenergetic Diet. *J Funct Morphol Kinesiol* (2019) 4(2):23. Epub 2019/04/25. doi: 10.3390/jfmk4020023. PubMed PMID: 33467338; PubMed Central PMCID: PMCPMC7739224.

25. Brewer GJ, Blue MNM, Hirsch KR, Saylor HE, Gould LM, Nelson AG, et al. Validation of InBody 770 bioelectrical impedance analysis compared to a four-compartment model criterion in young adults. *Clin Physiol Funct Imaging* (2021) 41(4):317-25. Epub 2021/03/23. doi: 10.1111/cpf.12700. PubMed PMID: 33752260.

26. Borg G. Percieved exertion as an indicator of somatic stress. *Scan J Rehabil Med* (1970) 2(2):92-8.

27. van Ingen Schenau GJ, Cavanagh PR. Power equations in endurance sports. *J Biomech* (1990) 23(9):865-81. Epub 1990/01/01. doi: 10.1016/0021-9290(90)90352-4. PubMed PMID: 2211732.

28. Péronnet F, Massicotte D. Table of nonprotein respiratory quotient: an update. *Can J Sport Sci* (1991) 16(1):23-9. Epub 1991/03/01. PubMed PMID: 1645211.

29. Winter DA. *Biomechanics and motor control of human movement*. 4 ed. Hoboken, New Jersey: John Wiley & Sons, Inc. (2009).

30. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *J Biomech* (1996) 29(9):1223-30. Epub 1996/09/01. doi: 10.1016/0021-9290(95)00178-6. PubMed PMID: 8872282.

31. Danielsen J, Sandbakk Ø, McGhie D, Ettema G. The effect of exercise intensity on joint power and dynamics in ergometer double-poling performed by cross-country skiers. *Hum Mov Sci* (2018) 57:83-93. Epub 2017/11/28. doi: 10.1016/j.humov.2017.11.010. PubMed PMID: 29179043.

32. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol* (2000) 10(5):361-74.

33. van den Tillaar R, Saeterbakken A. Effect of Fatigue Upon Performance and Electromyographic Activity in 6-RM Bench Press. *Journal of Human Kinetics* (2014) 40:57-65. Epub 2014/07/18. doi: 10.2478/hukin-2014-0007. PubMed PMID: 25031673; PubMed Central PMCID: PMCPMC4096084.

34. Ball N, Scurr J. Electromyography normalization methods for high-velocity muscle actions: review and recommendations. *Journal of Applied Biomechanics* (2013) 29(5):600-8.

35. Albertus-Kajee Y, Tucker R, Derman W, Lamberts RP, Lambert MI. Alternative methods of normalising EMG during running. *Journal of Electromyography and Kinesiology* (2011) 21(4):579-86.

36. Delacre M, Lakens D, Leys C. Why psychologists should by default use Welch's t-test instead of Student's t-test. *International Review of Social Psychology* (2017) 30(1).

37. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol* (2013) 4:863. Epub 2013/12/11. doi: 10.3389/fpsyg.2013.00863. PubMed PMID: 24324449; PubMed Central PMCID: PMCPMC3840331.

38. Cohen J. *Statistical power analysis for the behavioral sciences*. Erbaum Press, Hillsdale, NJ, USA (1988).

39. Noakes TD. Central regulation of skeletal muscle recruitment explains the reduced maximal cardiac output during exercise in hypoxia. *Am J Physiol Regul Integr Comp Physiol* (2004) 287(4):R996-R1002. doi: 10.1152/ajpregu.00608.2003. PubMed PMID: 15371281.

40. Holmberg HC, Lindinger S, Stöggl T, Björklund G, Muller E. Contribution of the legs to double-poling performance in elite cross-country skiers. *Med Sci Sports Exerc* (2006) 38(10):1853-60. Epub 2006/10/05. doi: 10.1249/01.mss.0000230121.83641.d1. PubMed PMID: 17019309.

41. Van Hall G, Jensen-Urstad M, Rosdahl H, Holmberg HC, Saltin B, Calbet JA. Leg and arm lactate and substrate kinetics during exercise. *American journal of physiology Endocrinology and metabolism* (2003) 284(1):E193-205. Epub 2002/10/22. doi: 10.1152/ajpendo.00273.2002. PubMed PMID: 12388120.

42. Calbet JA, Holmberg HC, Rosdahl H, van Hall G, Jensen-Urstad M, Saltin B. Why do arms extract less oxygen than legs during exercise? *Am J Physiol Regul Integr Comp Physiol* (2005) 289(5):R1448-58. Epub 2005/05/28. doi: 10.1152/ajpregu.00824.2004. PubMed PMID: 15919729.

43. Ortenblad N, Nielsen J, Boushel R, Soderlund K, Saltin B, Holmberg HC. The Muscle Fiber Profiles, Mitochondrial Content, and Enzyme Activities of the Exceptionally Well-Trained Arm and Leg Muscles of Elite Cross-Country Skiers. *Front Physiol* (2018) 9(AUG):1031. Epub 2018/08/18. doi: 10.3389/fphys.2018.01031. PubMed PMID: 30116201; PubMed Central PMCID: PMCPMC6084043.

44. Calbet JA, Jensen-Urstad M, van Hall G, Holmberg HC, Rosdahl H, Saltin B. Maximal muscular vascular conductances during whole body upright exercise in humans. *J Physiol* (2004) 558(Pt 1):319-31. Epub 2004/05/04. doi: 10.1113/jphysiol.2003.059287. PubMed PMID: 15121799; PubMed Central PMCID: PMCPMC1664902.

45. Losnegard T, Tosterud OK, Trøen E, Carlsen CH, Paulsen G, Rud B. The influence of pole lengths on O_2-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.

46. Berg J, Undebakke V, Rasch-Halvorsen Ø, Aakerøy L, Sandbakk Ø, Tjønna AE. Comparison of mitochondrial respiration in M. triceps brachii and M. vastus lateralis between elite cross-country skiers and physically active controls. *Front Physiol* (2019) 10:365.

47. Losnegard T. Energy system contribution during competitive cross-country skiing. *Eur J Appl Physiol* (2019) 119(8):1675-90. Epub 2019/05/12. doi: 10.1007/s00421-019-04158-x. PubMed PMID: 31076890; PubMed Central PMCID: PMCPMC6647095.

48. Ettema G, Lorås HW. Efficiency in cycling: a review. *Eur J Appl Physiol* (2009) 106(1):1-14. Epub 2009/02/21. doi: 10.1007/s00421-009-1008-7. PubMed PMID: 19229554.

49. Curran-Everett D. Explorations in statistics: the analysis of ratios and normalized data. *Adv Physiol Educ* (2013) 37(3):213-9. Epub 2013/09/12. doi: 10.1152/advan.00053.2013. PubMed PMID: 24022766.

50. Danielsen J, Sandbakk Ø, McGhie D, Ettema G. Mechanical energetics and dynamics of uphill double-poling on roller-skis at different incline-speed combinations. *PloS ONE* (2019) 14(2):e0212500. doi: DOI:10.1371.

51. Danielsen J, Sandbakk Ø, McGhie D, Ettema G. Mechanical energy and propulsion mechanics in roller-skiing double-poling at increasing speeds. *PLoS One* (2021) 16(7):e0255202. Epub 2021/07/29. doi: 10.1371/journal.pone.0255202. PubMed PMID: 34320011; PubMed Central PMCID: PMCPMC8318240.

52. Hill AV. The heat of shortening and the dynamic constants of muscle. *Proc Royal Soc B* (1997) 126(843):136-95. doi: 10.1098/rspb.1938.0050.

53. Zoppirolli C, Pellegrini B, Modena R, Savoldelli A, Bortolan L, Schena F. Changes in upper and lower body muscle involvement at increasing double poling velocities: an ecological study. *Scand J Med Sci Sports* (2017) 27(11):1292-9. Epub 2016/10/12. doi: 10.1111/sms.12783. PubMed PMID: 27726202.

Figure 1.TIFF

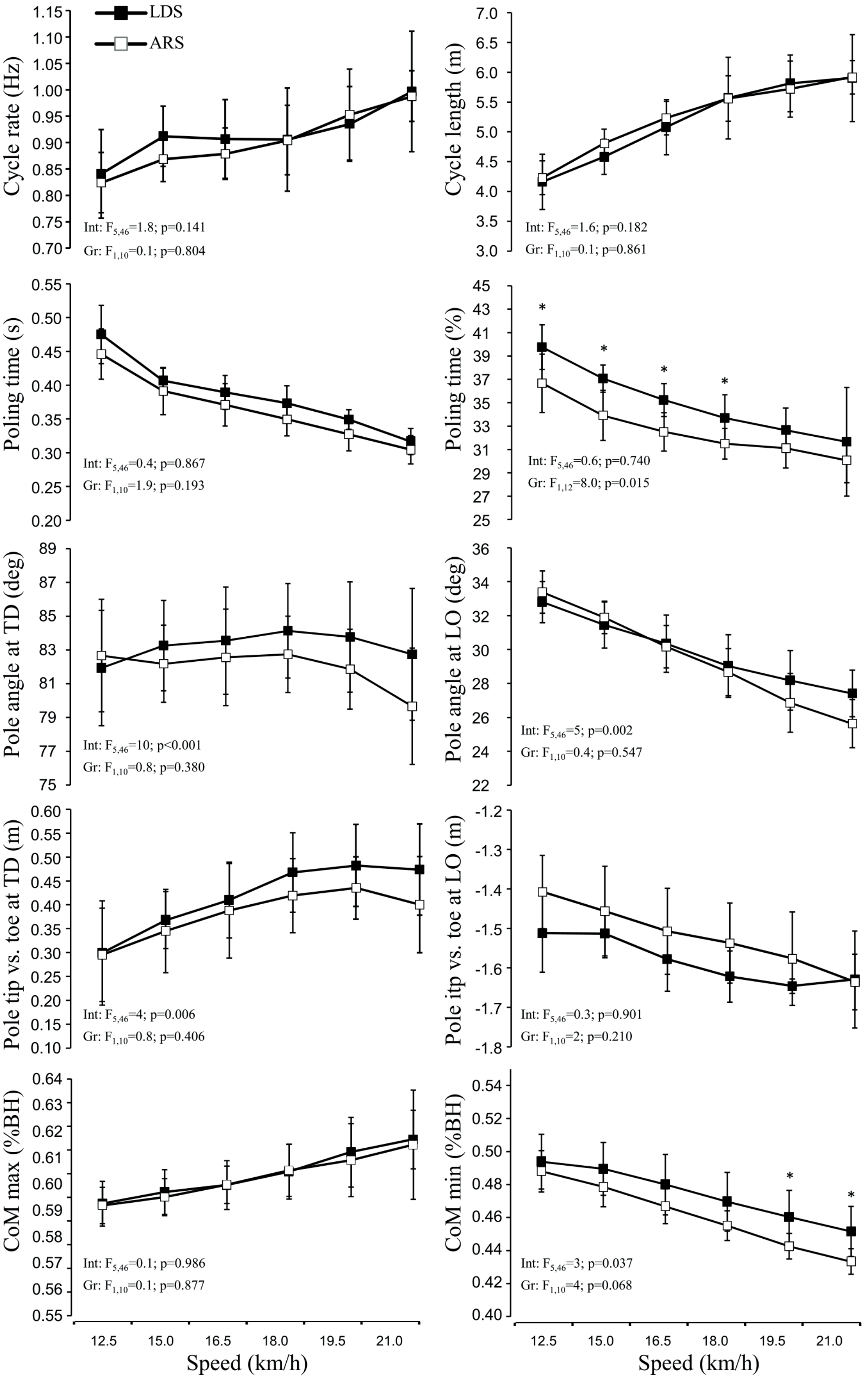


Figure 2.TIFF

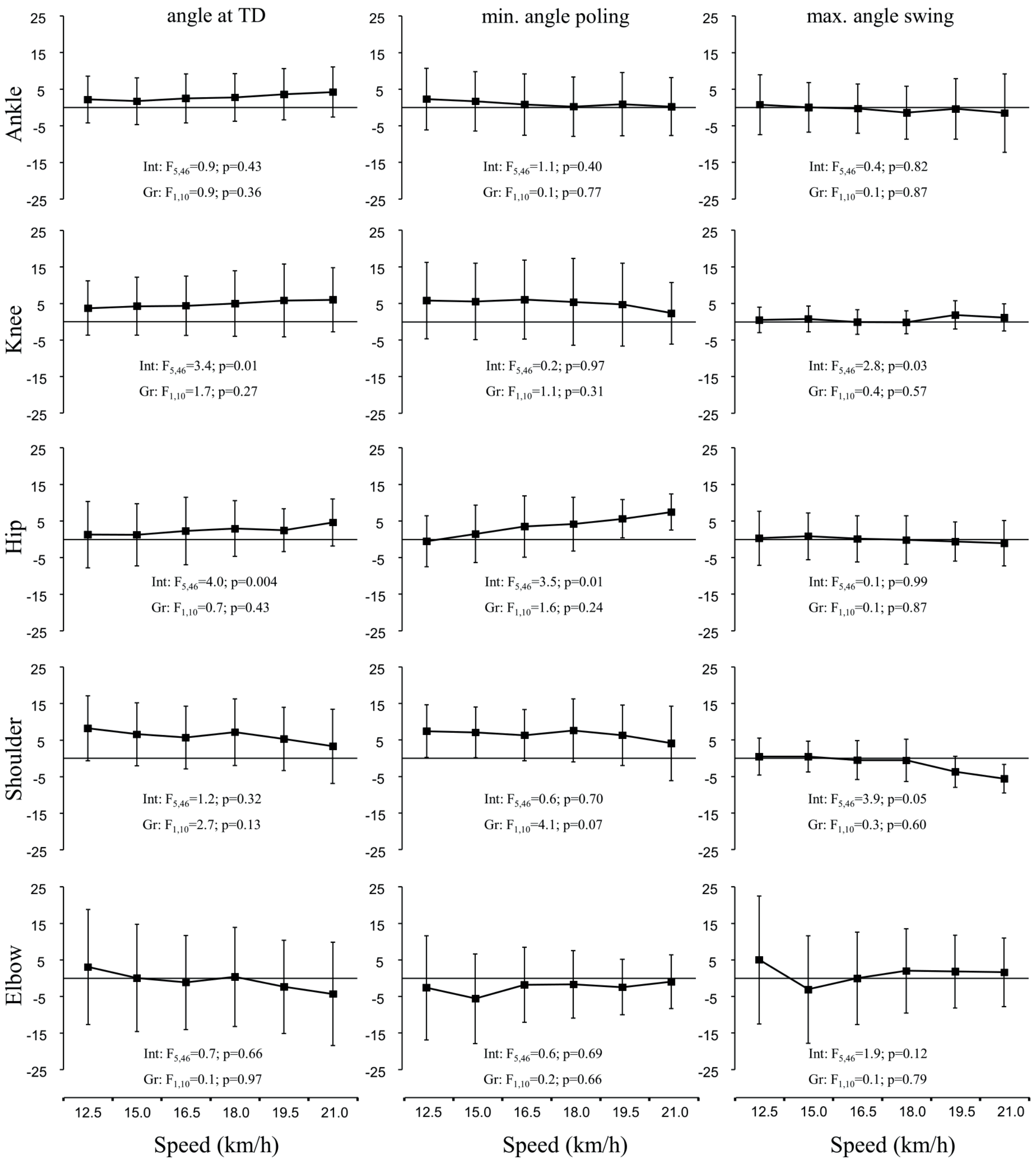


Figure 3.TIFF

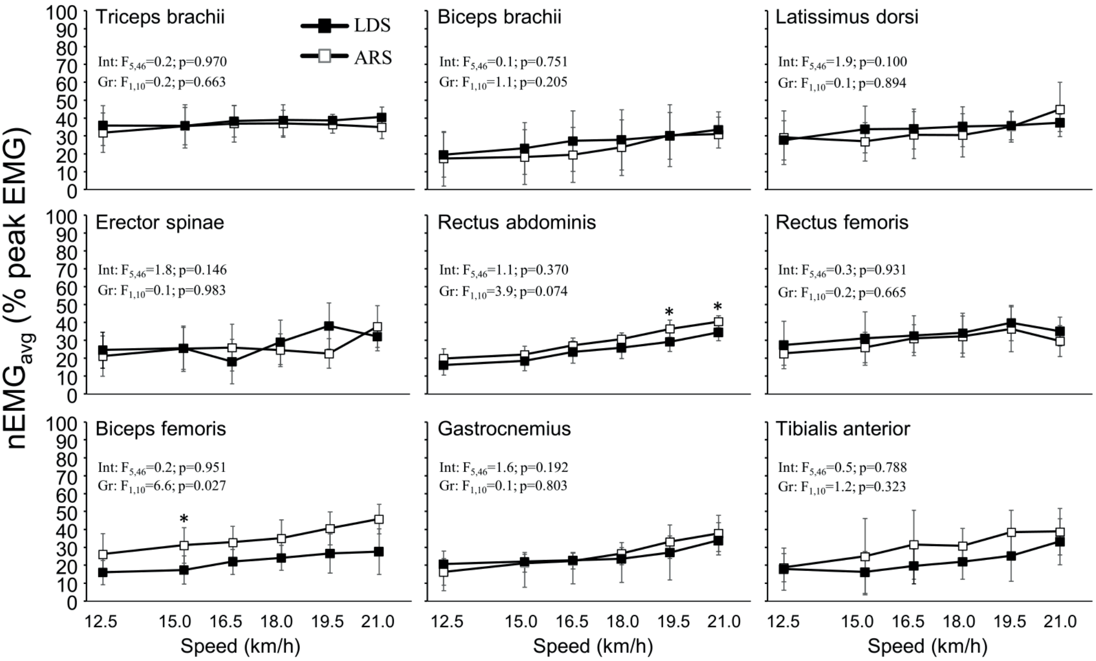
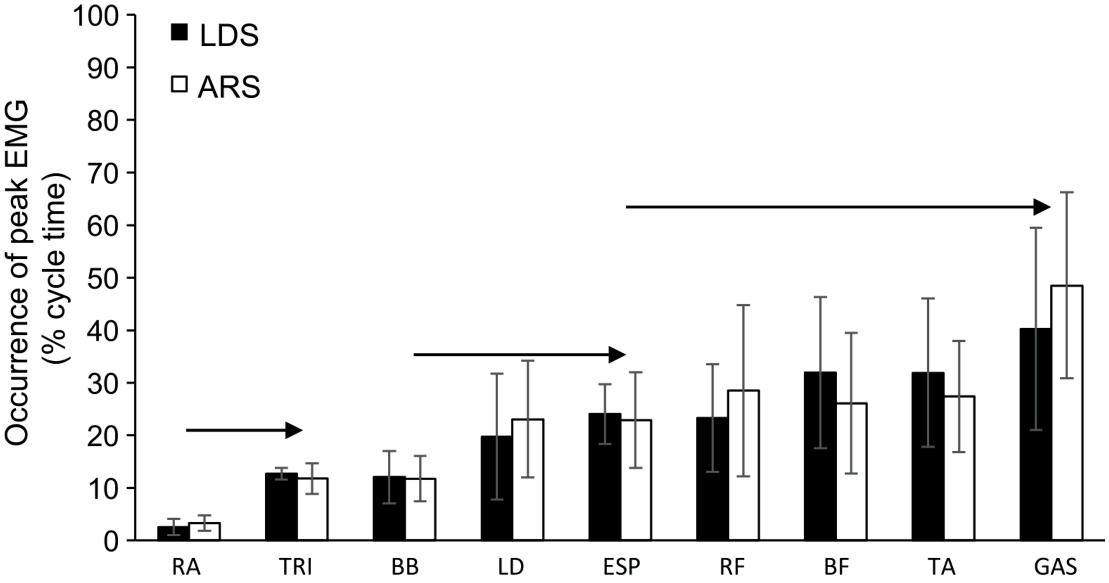


Figure 4.TIFF



Study II

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 25 February 2021
doi: 10.3389/fspor.2021.641389

The Training Characteristics of World-Class Male Long-Distance Cross-Country Skiers

Per-Øyvind Torvik[1]*, **Guro Strøm Solli**[1,2] **and Øyvind Sandbakk**[2]

[1] Department of Sports Sciences and Physical Education, Nord University, Levanger, Norway, [2] Department of Neuromedicine and Movement Science, Centre for Elite Sports Research, Faculty of Medicine and Health Sciences, Norwegian University of Science and Technology, Trondheim, Norway

Edited by:
Beat Knechtle,
Universitätsklinikum
Zürich, Switzerland

Reviewed by:
Thomas Haugen,
Kristiania University College, Norway
Dale Wilson Chapman,
New South Wales Institute of
Sport, Australia
Sarah J. Willis,
University of Lausanne, Switzerland
Glenn Björklund,
Mid Sweden University, Sweden
Chiara Zoppirolli,
University of Verona, Italy
Martin Burtscher,
University of Innsbruck, Austria

***Correspondence:**
Per-Øyvind Torvik
per.o.torvik@nord.no

Specialty section:
This article was submitted to
Exercise Physiology,
a section of the journal
Frontiers in Sports and Active Living

Received: 15 December 2020
Accepted: 21 January 2021
Published: 25 February 2021

Citation:
Torvik P-Ø, Solli GS and Sandbakk Ø
(2021) The Training Characteristics of
World-Class Male Long-Distance
Cross-Country Skiers.
Front. Sports Act. Living 3:641389.
doi: 10.3389/fspor.2021.641389

Purpose: To investigate the training characteristics of world-class long-distance cross-country skiers.

Methods: Twelve world-class male long-distance cross-country skiing specialists reported training from their best season, through a questionnaire and follow-up interviews. Training data were systemized by training form (endurance, strength, and speed), intensity [low- (LIT), moderate- (MIT), and high-intensity training (HIT)], and exercise mode, followed by a division into different periodization phases. Specific sessions utilized in the various periodization phases were also analyzed.

Results: The annual training volume was 861 ± 90 h, consisting of 795 ± 88 h (92%) of endurance training, 53 ± 17 h (6%) of strength training, and 13 ± 14 h (2%) of speed training. A pyramidal (asymptotic) endurance training distribution was employed (i.e., 88.7% LIT, 6.4% MIT, and 4.8% HIT). Out of this, 50–60% of the endurance training was performed with double poling (DP), typically in the form of a daily 3- to 5-h session. A relatively evenly distributed week-to-week periodization of training load was commonly used in the general preparation period, whereas skiers varied between high-load training weeks and competition weeks, with half the training volume and a reduced amount of DP during the competition period.

Conclusions: To match the specific demands of long-distance cross-country skiing, specialized long-distance skiers perform relatively long but few training sessions and use a pyramidal intensity distribution pattern and a large amount of training spent using the DP technique.

Keywords: XC skiing, endurance training, strength training, speed training, double poling

INTRODUCTION

Competitive cross-country (XC) skiing consists of two main types of event: (1) the Olympic disciplines, with competition formats ranging from short (~1.5 km) sprint competitions to 50-km-distance races performed in hilly terrain in the classical or skating styles, and (2) long-distance XC skiing with distances mainly ranging from 40 to 90 km performed in a more steady terrain and the majority of the races performed in the classical style.

While the Olympic disciplines include the use of and transition between many different subtechniques (Sandbakk and Holmberg, 2017; Solli et al., 2018, 2020), the relatively flat terrain profiles in long-distance events are often won on skis without grip wax, using solely the double-poling (DP) subtechnique (Sagelv et al., 2018; Zoppirolli et al., 2018, 2020; Skattebo et al., 2019; Stöggl et al., 2020) As a consequence of these demands and the increasing popularity of long-distance XC skiing, such as the Visma Ski Classics (VSC) series, long-distance XC skiers have fully specialized their training for performance in long-distance events (Skattebo et al., 2019). However, in contrast to the detailed examinations of physiological profiles and training characteristics of Olympic XC skiers (Sandbakk et al., 2011, 2016; Tønnessen et al., 2014; Sandbakk and Holmberg, 2017; Solli et al., 2017), these factors have been almost unexplored among skiers who have specialized in long-distance XC.

Extensive use of the DP subtechnique in long-distance races requires a well-developed DP technique, as well as upper-body strength and endurance capacity. A recent study compared the physiological capacities in DP between long-distance and Olympic XC skiers (Skattebo et al., 2019). While the study showed similar DP performances (i.e., time-to-exhaustion), long-distance skiers had lower peak oxygen uptake [maximal aerobic capacity ($\mathrm{VO}_{2\mathrm{peak}}$)] and better skiing efficiency (i.e., lower O_2 cost) than Olympic skiers (Skattebo et al., 2019). Furthermore, Sagelv et al. (2018) reported that long-distance skiers performed better in DP than Olympic XC skiers and had lower blood lactate concentration, heart rate, and rating of perceived exertion at submaximal workloads due to higher DP efficiency. Accordingly, these findings may imply that the training of long-distance XC skiers, which includes more focus on DP than for Olympic XC skiers, leads to superior DP efficiency but lower $\mathrm{VO}_{2\mathrm{peak}}$.

The only scientific report on training in long-distance XC skiers is from the study of Skattebo et al. (2019), who reported an annual training volume of 775 h, distributed as 83% low-intensity (LIT), 3% moderate-intensity- (MIT), 6% high-intensity (HIT), 7% strength, and 2% speed training. This is within the range of training distribution reported for world-class Olympic XC skiers, with 750–950 h of annual training volumes distributed as 90–95% endurance training, 5–10% strength training, and 1–2% speed training (Sandbakk et al., 2011, 2016; Tønnessen et al., 2014; Solli et al., 2017). The endurance training intensity distribution observed in these elite Olympic XC skiers consisted of 88–91% LIT, 3–7% MIT, and 4–6% HIT, with an equal focus on classical and skating styles (Sandbakk et al., 2011, 2016; Losnegard and Hallén, 2014; Tønnessen et al., 2014; Solli et al., 2017). Although the training intensity distribution seems relatively similar, we would expect long-distance skiers to include more DP in their training, higher focus on flat terrain, and the inclusion of sport-specific sessions to meet the demands of long-distance XC skiing. However, such detailed information about the training characteristics of long-distance XC skiers is currently lacking. Although a recent study from Knechtle and Nikolaidis (2018) showed that ultramarathoners trained higher volumes at slower speeds than marathoners, detailed training data from long-distance and ultra-endurance athletes, including possible differences to the training of athletes competing in shorter events, are also lacking in other sports.

Therefore, the aim of this study was to investigate the training characteristics of world-class long-distance XC skiers, including detailed information about the distribution of training volume, intensity, and exercise modes, as well as specific session designs employed during the skiers' most successful season.

METHODS

Participants

Twelve male Norwegian and Swedish long-distance XC specialists were recruited between May and September 2020. The inclusion criteria were as follows: (1) having competed in the VSC for at least 3 years, (2) having achieved at least two podium performances during their career, and (3) having achieved at least one podium performance during their most successful season. Participants reported that their best season occurred between 2010 and 2019 and thus reported the training from the nominated season. All skiers had progressively built up their training by using traditional Olympic XC ski training, as described by Sandbakk and Holmberg (2017). Five of the participants had retired as athletes, whereas seven were still competing at an elite level. The participants achieved a total of 154 podium performances in the VSC races (range per athlete: 2–27), and seven of these also had podium performances in the International Ski Federation World Cup. The other five did not reach a top national level in Olympic XC skiing before they started preparing for long-distance races.

The Regional Committee for Medical and Health Research Ethics, Trondheim, Norway, waives the requirement for ethical approval for studies of this type. Therefore, the ethics of the study were according to the institutional requirements, whereas approval for data security and handling was obtained from the Norwegian Center for Research Data. Prior to data collection, all participants provided written informed consent to voluntarily take part in the study. The participants were informed that they could withdraw from the study at any time without providing a reason for doing so. The characteristics of the participants are presented in **Table 1**.

Questionnaire

Data were collected via an online questionnaire (Nettskjema: https://nettskjema.no/) based on previous detailed training analyses of world-class XC skiers (Solli et al., 2017) and adjusted to the study aim by an expert panel of former athletes, coaches, a physiologist, and researchers with experience from similar projects. The questionnaire contained an introduction part including detailed description on how to answer the questionnaire, and each question was appropriately defined to avoid misinterpretation. To ensure that participants understood the questions, a pilot study with three participants was conducted before data collection commenced.

Abbreviations: CP, Competition period; GP, General preparation period; HIT, High-intensity training; MIT, Moderate-intensity training; LIT, Low-intensity training; SP, Specific preparation period; VSC, Visma Ski Classics; XC, Cross country.

TABLE 1 | Anthropometric, physiological, and performance characteristics of 12 male long-distance cross-country skiers (mean ± SD) during their most successful season.

Variable	Value
Age, y	30.4 ± 3.7
Body height, cm	182.7 ± 5.6
Body mass, kg	77.0 ± 6.3
Body mass index, kg · m^{-2}	23.1 ± 1.1
Maximum heart rate, beats · min^{-1}	189 ± 8
Vo_2max, L · min^{-1}	6.2 ± 0.5
Vo_2max, mL · min^{-1} · kg^{-1}	80.1 ± 3.6
Total standing VSC	5.8 ± 7.5
FIS points (distance)*	24.5 ± 18.2
FIS points (sprint)*	55.3 ± 45.7

Vo_{2max}, maximal aerobic capacity; VSC, Visma Ski Classics; FIS, International Ski Federation.

**Lowest FIS points reported during the athlete's career.*

Designed to take 60–90 min to complete, the questionnaire contained 93 questions: zero closed-ended questions, 61 questions asking for a numeric value, one yes-or-no question, three multiple-choice questions, and 26 open-ended questions. Participants reported their demographic information, performance, and training characteristics during their most successful year in the VSC. The questionnaire also contained questions about their detailed design of typical training sessions used to meet the demands of the races in the VSC. During the data analysis, the participants were contacted to ensure compliance with the questionnaire responses and to verify the design and/or content of different training sessions.

All the recruited athletes completed the questionnaire, and their data were included in the final analysis. Ten of the athletes reported that their numeric data were collected from training diaries, while the remaining athletes reported training information from written notes. Because the questionnaire was in Norwegian, a translation process was performed to ensure validity when interpreting the questions in English.

Annual Periodization

All training data were organized into periods [general preparation period (GP: May–August), specific preparation period (SP: September–November), and competition period (CP: December–April)], training form (endurance, strength, and speed), and intensity (LIT, MIT, and HIT). LIT refers to a training intensity below the first lactate threshold (LT^1) (<2 mM blood lactate, 60–82% of maximal heart rate; HR_{max}), MIT refers to an intensity between LT^1 and LT^2 (2–4 mM blood lactate, 82–87% of HR_{max}), and HIT refers to an intensity above LT^2 (>4 mM blood lactate, >87% of HR_{max}) (Seiler and Kjerland, 2006). The participants used a combination of the session-goal approach and time in training zone to register training time, often called a modified session-goal approach as described in detail by Sylta et al. (2014). Strength training was categorized as heavy strength training and core stabilization (including muscular endurance). Speed training included maximal efforts of 10- to 20-s sprints or series of 10–15 plyometric jumps using ski specific movements. The use of exercise modes was categorized as being specific (DP on a ski ergometer or skiing/roller skiing) or other exercise modes. An overview of the annual cycle in long-distance XC skiing is presented in **Figure 1**.

Statistics

Questionnaire responses were summarized in numerical values to facilitate statistical analysis.

Continuous variables are presented as mean ± SD and were examined for the assumption of normal distribution prior to analysis using a Shapiro-Wilk test, visual inspection of Q–Q plots, and histograms. Categorical variables are presented as absolute numbers and percentages. Data were processed and analyzed using IBM SPSS Statistics version 24 software for Windows (SPSS Inc., Chicago, IL, USA) and Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA). A one-way repeated-measures analysis of variance was used for analyzing the differences in training across GP, SP, and CP. *Post hoc* comparisons were made using a Holm-Bonferroni correction. In cases where Mauchly test of sphericity indicated that the assumption of sphericity was violated, a Greenhouse–Geisser correction was performed. A $P \leq 0.05$ was considered statistically significant. Effect size was evaluated with η^2, where $0.01 < \eta^2 < 0.06$ constitutes a small effect, $0.06 < \eta^2 < 0.14$ constitutes a medium effect, and $\eta^2 > 0.14$ constitutes a large effect (Cohen, 1988). To categorize free-text questions, two researchers performed independent content, frequency, and consistency analyses until consensus was reached. Direct verbatim quotations were used to inform interpretation. Descriptive data for continuous variables were recorded as means (SD), and for categorical variables as totals and percentages. For continuous variables, the Shapiro–Wilk test and standard visual inspection were used to examine the assumption of normality.

RESULTS

The annual training volume was 861 ± 90 h, consisting of 795 ± 88 h (92%) endurance training, 53 ± 17 h (6%) strength training, and 13 ± 14 h (2%) speed training. Periodical training patterns across the different period of the annual cycle are presented in **Figure 2A**. There was a change in training volume across period (GP: 85 h, SP: 87 h, and CP: 75 h; $P = 0.017$, $\eta^2 = 0.350$) with the training volume being significantly higher in GP ($P = 0.024$) and SP ($P = 0.011$) compared to CP.

All athletes reported to normally use a traditional periodization model with a relatively even week-to-week distribution of training load (including the use of endurance and strength/speed training) during GP. Accordingly, their microcycle periodization was modest, and they kept training volumes high (i.e., 20–25 h/wk) for 2–3 weeks followed by a week with lower training load every 3–4 weeks or when they perceived a need for restitution. The competitive season for long-distance skiers lasts until late April, which requires a period of less training in May and beginning of June followed by a gradual progression of both training volume and intensity from June to September. Two of the athletes reported a strict microperiodization system

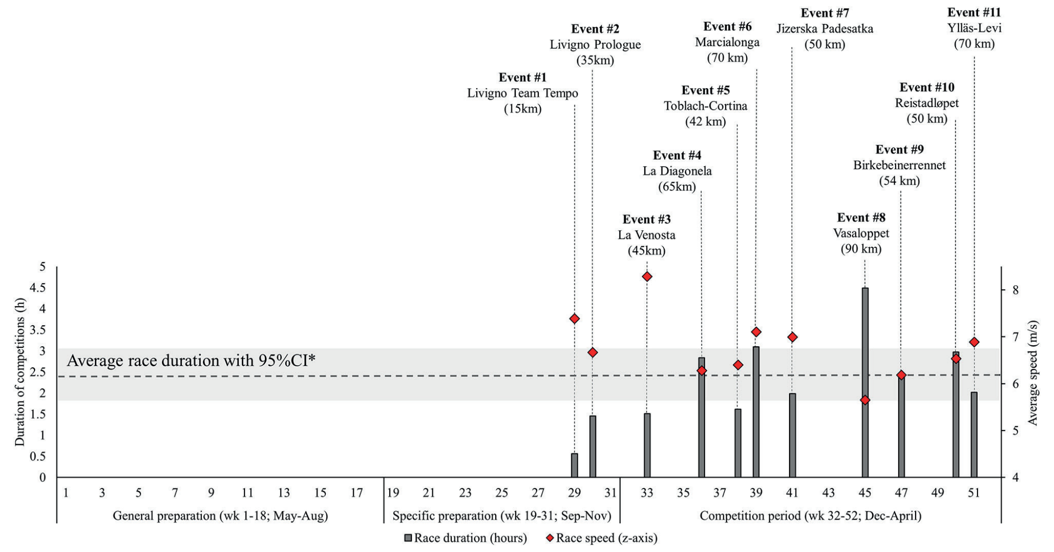


FIGURE 1 | Illustration of the annual cycle in long-distance XC skiing with the timing of the competitions in the Visma Ski Classic 2019. Competition duration and speed are calculated based on the average for the three best skiers in each race and the course length reported in the official result lists (www.vismaskiclassics.com) of the 2018–2020 seasons. *The Livigno Team Tempo is excluded from the calculation of average race duration (dotted line) with 95% CI (gray area).

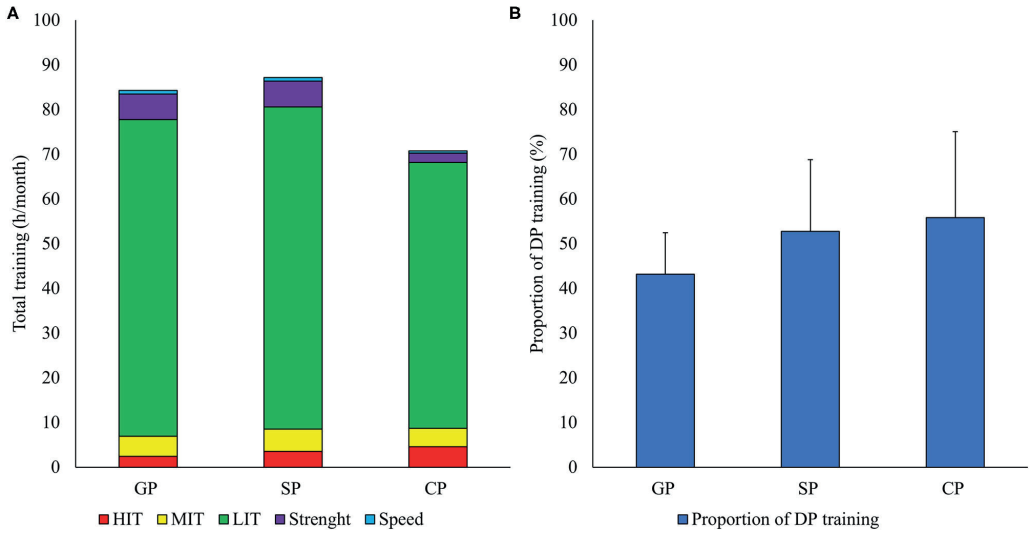


FIGURE 2 | Training distribution **(A)** across the annual period [general preparation period (GP: May–August), specific preparation period (SP: September–November), and competition period (CP: December–April) during the athletes' most successful seasons distributed as endurance [low- [LIT], moderate- [MIT], and high-intensity [HIT]], strength, and speed training, as well as the proportion of training using the double poling (DP) subtechnique **(B)** for world-class long-distance cross-country skiers.

consisting of 5/2 and 7/1 training/resting days. Five skiers reported some blocks with emphasis on specific qualities during the GP; three skiers included a couple of blocks of strength training, two had a few blocks of DP training, and one reported one to three blocks of increased amounts of HIT (5 HIT sessions in 6 days). All athletes reported more structured and accurate intensity control in SP than in GP. The same accurate intensity control was maintained during CP, but the training volume/load was determined by the competition schedule, with 10–12 h of weekly training in weeks with competitions and 20–30 h during weeks without competitions.

Endurance Training

Annual LIT, MIT, and HIT volumes were 706 ± 92, 51 ± 24, and 39 ± 24 h, respectively, corresponding to an intensity distribution consisting of 88.7 ± 4.8% LIT, 6.4 ± 2.7% MIT, and 4.8 ± 2.8% HIT (including competitions). No significant differences between period were observed for LIT (GP: 71 h, SP: 72 h, and CP: 63 h; $P = 0.071$, $\eta^2 = 0.214$) or MIT volume (GP: 4.5 h, SP: 5.0 h, and CP: 4.1 h; $P = 0.034$, $\eta^2 = 0.093$). However, HIT volume (GP: 2.4 h, SP: 3.5 h, and CP: 4.6 h; $P = 0.010$, $\eta^2 = 0.342$) was significantly higher in CP compared to GP ($P = 0.017$).

Strength and Speed Training

The periodical volume of strength training was significantly different between the annual period (GP: 5.7 h, SP: 5.8 h, and CP: 2.1 h; $P < 0.001$, $\eta^2 = 0.590$), with the strength volume being lower in CP compared to both GP ($P < 0.001$) and SP ($P = 0.009$). The proportion of heavy training vs. core stabilization training was relatively stable across GP (63 vs. 37%), SP (63 vs. 37%) and CP (65 vs. 35%). No difference in speed training was observed between the annual period (GP: 0.8 h, SP: 0.8 h, and CP: 0.5 h; $P = 0.368$, $\eta^2 = 0.087$).

Exercise Modes

A total of 48 ± 13% of endurance and speed training was conducted as DP (ski ergometer, roller skiing, and skiing). The amount of DP training (GP: 43% h, SP: 53%, and CP: 56% h; $P = 0.013$, $\eta^2 = 0.328$) was significantly higher in SP ($P = 0.049$) and CP ($P = 0.041$) compared to GP (**Figure 2B**). Examples of the most used sport-specific training sessions and representative training weeks through the annual season is presented in **Tables 2**, **3**.

DISCUSSION

This study investigated the training characteristics of world-class male long-distance XC skiers during their most successful season, including detailed information about training volume, intensity distribution, exercise modes, periodization, and session designs. The main findings were as follows: the average annual training volume was 861 ± 90 h, including 795 h (92%) of endurance training, 53 h (6%) of strength training, and 13 h (2%) of speed training. Here, a pyramidal (asymptotic) endurance training distribution was employed (i.e., 88.7% LIT, 6.4% MIT, and 4.8% HIT), with 50–60% of the endurance and speed training performed using DP. This training included many long-distance sessions, typically performed as a daily 3- to 5-h session. The week-to-week periodization of endurance training load was relatively evenly distributed in GP and SP, while all the skiers maintained a high training volume during training weeks in the CP but halved their volume and reduced the amount of DP during weeks with competitions.

The average annual training volume of 861 ± 90 h performed by the skiers in this study is in line with the 750–950 h previously observed in Olympic distance XC skiers (Sandbakk and Holmberg, 2014, 2017). Also, in line with Olympic XC skiers, more than 90% of this overall volume of the long-distance XC skiers was endurance training, with the intensity distributed in a pyramidal pattern (i.e., 89% LIT, 6% MIT, and 5% HIT) (Stöggl and Sperlich, 2015). As previously reported for all successful XC skiers (Sandbakk and Holmberg, 2017), the most training was LIT, which is considered to provide an important foundation for long-term endurance adaptations, by increasing tolerance for high volumes of training without being injured or overloaded, as well as complementing training at higher intensities (Laursen, 2010; Sandbakk and Holmberg, 2017). However, the pyramidal distribution is related to more MIT than previously reported in Olympic XC skiers, who normally show a more polarized intensity distribution (Sandbakk and Holmberg, 2014, 2017), probably due to differences in competition demands. Large endurance training volumes, with the majority performed as LIT, are common among endurance and ultra-endurance athletes across sports (Knechtle and Nikolaidis, 2018). While studies from a range of endurance sports show either polarized or pyramidal intensity distributions (Stöggl and Sperlich, 2015), the intensity distribution of long-distance or ultra-endurance is currently lacking in the literature.

Most long-distance races are performed with DP in relatively even terrain, which is similar to the demands of longer-duration MIT sessions performed with DP common among long-distance XC skiers. This is supported by the latest research (Stöggl et al., 2020), who found the mean race intensity to be 82% of maximal heart rate during a long-distance skiing event. The training routines of long-distance specialists consist of relatively high training volumes (i.e., >850 h per year) with a pyramidal endurance intensity.

The skiers studied here performed MIT sessions about once or twice per week during GP and SP, but mainly in competition-free weeks in CP, as recovery of the arms and upper body was prioritized before competitions. Specifically, these MIT sessions were performed using DP, either with long intervals (8–15 min) with short breaks (1–2 min) or as continuous 45- to 75-min sessions. Such sessions aim to delay the duration-related fatigue of long-distance races, which leads to reduced coordination, and this directly or indirectly affects the ability to maintain muscle power throughout the competition (Zoppirolli et al., 2018).

During CP, most of the reported HIT time came from competitions. However, many HIT sessions performed by the long-distance skiers during GP and SP were designed to simulate the competitive demands of certain important races. This concept is similar to Olympic XC skiing, where the specialized

TABLE 2 | Sport-specific training methods for long-distance XC skiing, categorized as continuous, mixed, and interval-based training sessions.

	Training method	Exercise modes	Description
Continuous training	Long-distance specific	DP	3–8 h DP sessions, flat, and undulating terrain, with or without inclusion of sprints (10 × 10–12 s)
	Long-distance non-specific	All	2–4 h Low-intensive steady-state running, skating, or classic skiing on undulating terrain
	Long-distance mix of exercise modes	All	Low-intensive steady-state sessions changing the exercise mode in midsession. For instance, 2 h DP + 2 h running
	Progressive long distance	DP	Progressive session starting with 1.5–2.5 LIT followed by 0.5- to 1.15-h MIT and 0.5-h HIT Progressive 2- to 4-h session interspersed with sprints, and maximal effort during one uphill at the end of the session
	Competitions/tests or simulated competitions	DP Running	Competitions or test races ranging from 30 min to 2 h, often simulating the terrain of one of the main races during CP
Mixed training sessions	LIT + intervals	DP	2- to 5-h LIT followed by an interval session at moderate and/or high intensity. Typical sessions (5–6 × 5–6 min, 15 × 3 min, 30 × 1 min, 5 × 2 min, 45/15 s in 30 min)
	Interval + LIT	DP	Session started with an MIT or HIT interval (examples below), followed by 2- to 3-h LIT to simulate the fast start in races
	Strength + LIT	DP	2- to 4-h LIT before, during or after a strength session (heavy strength training + muscular endurance as described below)
Interval training sessions	MIT intervals	DP DIA Running	0.5- to 1-h warm-up followed by intervals at moderate intensity. Typical sessions: 4–6 × 8–15 min, 10 × 5–6 min, 15 × 3 min with 1–2 min recovery between intervals
	HIT intervals	DP Running DIA Running with poles	0.5- to 1-h warm-up followed by intervals at high intensity. Typical sessions: 4–6 × 4–6 min uphill, 5 × 10 min undulating terrain, 10 × 2–3 min with 2–3 min recovery between intervals. Short intervals such as 3–5 × 8–10 min (40/20 s, 45/15 s or 30/15-s work/rest with 2-min rest between intervals)
	Competition preparations	DP	0.5- to 1-h warm-up followed by intervals at high intensity often in easy terrain, to achieve high speed. Typical session: 4 × 6 min, 5–4–3–2–1 min, 3 × (3–2–1 min), with 1- to 3-min rest between intervals
	Lactate production training	DP	0.5- to 1-h warm-up followed by intervals at maximal effort. Typical sessions: 10–20 × 1 min with 1- to 3-min rest between intervals, 3 × (6 × 1 min), with 2-min rest between intervals, and 5-min rest between series
Strength & speed	Heavy strength		5 × 5 repetitions of 5–7 sets using exercises such as deadlift, squat, clean, pull-down, chins, toes to bar, back extension, pull over, dips, bench press (narrow grip)
	Muscular endurance		5–10 series of 6–12 repetitions with relatively short rest (1 min) between sets. Typical session: 10 × 10 repetitions of chins with start every minute or series of 1–2–3–4–5–6–7–8–9–10–9–8–7–6–5–4–3–2–1 repetitions, with start every minute
	Core stabilization		20–50 repetitions of different exercises targeting core stabilization or 45/15-s work/rest for 20–30 min using different exercises involving red core (slings), Olympic rings, elastic bands, and medicine balls
	Sprints	DP	10–15 × 10–15 s maximal effort, typically during long-distance LIT sessions with 2- to 3-min active recovery between sprints

All, all exercise modes; DP, double poling; DIA, diagonal stride; LIT, low-intensity endurance training; MIT, moderate-intensity endurance training; HIT, high-intensity endurance training; CP, competition period.

HIT sessions target the demands of either sprint or distance skiing disciplines (Sandbakk and Holmberg, 2017). An example highlighted in this study was a skier who focused mainly on Vasaloppet reported that he started many sessions with 1 h of MIT, followed by 2 h of LIT, before finishing with 30–40 min of HIT. Other skiers describe similar approaches prior to winning the Marcialonga where they finished the LIT training sessions with a 15-min HIT using DP on steep uphill terrain, simulating the 3-km final uphill finish in this particular race. Both examples show how the MIT/HIT session designs are guided by the competition demands.

In addition, regular HIT sessions were performed to increase participants' general aerobic capacity, such as short intervals from 45 s to 5 min with 15-s to 3-min recovery periods. Many of these sessions were in a non-specific training mode, such as diagonal stride, running, or running with poles to recover the arms while stimulating their $\dot{V}O_{2max}$. In this context, all skiers studied had a history of training for Olympic XC skiing and

TABLE 3 | Representative training week examples through the annual season for long-distance cross-country skiers.

Day	General preparation period (GP)	Specific preparation period (SP)	Competition period (CP)[†]
Mon	M: 3-h LIT long-distance DP[*] E: 1- to 1.5-h LIT long-distance running	M: 3-h LIT long-distance DP, with sprints E: 1- to 1.5-h LIT long-distance running	M: 2-h LIT long-distance DP, with sprints E: Rest
Tue	M: 3.5-h LIT long-distance running E: Rest	M: 4-h LIT long-distance running E: Rest	M: 3-h LIT long-distance DP E: 1-h LIT long-distance running
Wed	M: 1-h LIT warm-up 1-h MIT intervals in DP[‡] (5 × 10 min) 1-h LIT cool-down E: 1h Strength training: Core stabilization and heavy strength	M: 1-h LIT warm-up to 1.15-h MIT DP (Continuous) 1-h LIT cool-down E: Rest	M: 0.5-h LIT warm-up 1-h MIT intervals in DP (6 × 8 min) 0.5-h LIT cool-down E: 1-h Strength training: Core stabilization and muscular endurance
Thu	M: 2-h LIT long-distance running E: Rest	M: 4-h LIT long-distance DP followed by 1 h muscular endurance and heavy strength training E: Rest	M: 3-h LIT long-distance DP E: Rest
Fri	M: 3-h LIT long-distance DP, with sprints E: Rest	M: 2-h LIT long-distance DP, with sprints E: Rest	M: 3-h LIT long-distance mix of exercise modes (Classic, Skating and DP) E: Rest
Sat	M: 2-h LIT DP 0.6-h MIT intervals in DP (6 × 5 min) 0.5-h LIT cool-down E: 1 h Heavy strength training	M: 0.5-h LIT warm-up 0.8-h HIT intervals running with poles (7 × 4 min) 0.5-h LIT cool-down E: Rest	M: 0.5-h warm-up 0.8-h HIT intervals treadmill running (6 × 5 min)[§] 0.5 h cool-down E: Rest
Sun	M: 2- to 3-h LIT running, with sprints E: Rest	M: 2–3-h LIT long-distance DP, with sprints E: Rest	M: 4-h LIT long-distance DP, with sprints E: Rest
Total	Volume: 15–24 h Sessions: 5–10 Distribution: 87/4/0 % LIT/MIT/HIT	Volume: 22–25 h Sessions: 5–10 Distribution: 88/3/3 % LIT/MIT/HIT	Volume: 17–25 h Sessions: 5–10 Distribution: LIT 87/5/4 % LIT/MIT/HIT

[*] The LIT sessions varied from athlete to athlete in GP, from 2 to 5 h, and the evening training depended on the duration of the morning training. [‡] The MIT intervals were organized in different ways throughout the year, from 8 to 15 min with 1- to 2-min break and lasting from 45 to 75 min. [†] The training example is from a week without a Visma Ski Classic race. [§] During SP and CP, the athletes increased intensity into the area between MIT and HIT to keep up their maximal aerobic power, and they used non-specific modes for arm recovery. M, morning training; E, evening training; DP, double pooling; LIT, low-intensity endurance training; MIT, moderate-intensity endurance training; HIT, high-intensity endurance training.

had an average $\dot{V}O_{2max}$ of $\sim$80 mL $\cdot$ min^{-1} $\cdot$ kg^{-1} in their best year as a long-distance skier. The previous focus on Olympic XC skiing may have led to the development of a high maximal aerobic capacity (Holmberg, 2015) that can be maintained with smaller amounts of HIT when specializing in long-distance XC skiing, and greater focus on long-duration LIT and MIT sessions.

After reduced training load in May and beginning of June, a gradual progression of both training volume and intensity from June to September was present in these long-distance skiers. The week-to-week periodization of this training load, including the distribution of LIT, MIT, and HIT, was relatively evenly distributed in GP and SP, with an overall reduction of training volume during CP. Although a few skiers included a few blocks of strength training or focus on the DP mode, block periodization was not greatly used and not systematically as previously described for some seasons of the most successful female skier in history (Solli et al., 2017). In CP, all skiers had a pronounced periodization pattern, where high-volume training weeks were followed by competition weeks with half of the usual training load and less strain on the upper body to ensure muscular fitness for the competitions.

Accordingly, these long-distance skiers used a traditional periodization model, which emphasizes a mixed focus on training forms and intensities during all periods across the annual season, but with a progressive reduction in training volume substituted by higher training intensity and more specific training toward the CP (Matwejew, 1975; Tønnessen et al., 2014). Although several successful endurance athletes have organized their training according to this (Tønnessen et al., 2014, 2015; Rasdal et al., 2018; Solli et al., 2019), the model has received criticism because of the possible conflicting physiological responses produced by mixed training directed at many performance-related factors at the same time (Issurin, 2008). As an alternative, it has been suggested that a more effective way of organizing endurance training is to include defined blocks of increased focus on specific intensities, such as block periodization of HIT (Issurin, 2008).

More than 50% of the endurance training of the skiers was performed with DP, which is exceptionally high compared to Olympic XC skiers, who execute 50–60% of their endurance training in all specific exercise modes, including skiing in four to six subtechniques in both classical and skating styles (Sandbakk and Holmberg, 2017). In contrast, 50–60% of the endurance training of the skiers studied is in one specific subtechnique. This means that $\sim$400–450 h per year were performed using DP, which is probably more than double the volume performed by Olympic XC skiers.

The high amount of DP in long-distance skiers may benefit their DP endurance capacity and technique in a wide range of different terrains and speeds. Consequently, Sagelv et al. (2018)

and Skattebo et al. (2019) demonstrated better DP performance due to better DP efficiency, despite equal or lower $\text{V}\text{O}_{2\text{peak}}$, in long-distance skiers than in Olympic skiers. In addition, previous research has shown that O_2 extraction in the upper body of XC skiers approaches that of the legs (Calbet et al., 2005). However, the high volume of upper-body training using the DP mode in long-distance XC skiers may allow them to extract more O_2 from the upper body than shown in previous research on Olympic XC skiers.

Many of these DP sessions were relatively long (3–5 h) LIT sessions, and up to 8 h were reported by some skiers. In addition to being specific for the demands of long-distance XC skiing, these extended LIT sessions may provide a positive supplement to their previous training as Olympic XC skiers. Similar approaches have been used for decades by cyclists (Faria et al., 2005). However, there is a limit to the amount of DP a skier can tolerate, and as one skier in this study stated, "It is also a question of how much DP you can endure, without having motivational problems, injuries, or other setbacks."

Giving priority to extended sessions requires longer recovery and often only one session each day. Consequently, fewer sessions are performed by long-distance XC specialists than by Olympic XC skiers, who normally have shorter sessions twice per day. The long-distance skiers who reported training two sessions per day used a shorter second session as active recovery, often in a non-specific training mode.

Strength and speed training are performed concurrently to this large amount of endurance training, and previous literature shows this to be beneficial for endurance performance through several mechanisms such as maintaining muscle mass, improving work economy/efficiency, and delaying fatigue during long-distance competitions (Sandbakk, 2018). However, only a certain level of strength is required, as one skier stated, "The goal of strength training is to become strong enough." In this context, compared to previous data on Olympic skiers (Sandbakk and Holmberg, 2017), the total volume of strength training (6%, 53 h) reported was similar, whereas the amount of speed training (2%, 13 h) was lower.

Generally, the skiers placed strength training sessions in their schedule based on the goal of the session, e.g., strength training performed after a LIT session aimed to fatigue the upper body muscles with long-term LIT before mobilizing the specific muscles with strength exercises. Other sessions were aimed at developing movement-specific power and therefore took place directly after warm-up. As for types of strength exercises, the athletes agreed that upper-body and core exercises aimed at developing power in the DP movement were most important, with chins as an example of an exercise used by all athletes. Block periodization of strength training was only reported only by a few athletes, but several pointed out the importance of building up their strength early in the cycle to become "strong enough" to tolerate all the DP without getting injured.

Sessions mainly focused on speed training were not prioritized by long-distance specialists, but all participants reported having regularly included 5–10 short sprints in their LIT sessions. Such sessions target their ability to accelerate and maintain high speed during attacks or when they were in position to fight for victory at the end of a race. Therefore, these sessions are often performed at the end of LIT sessions. In addition, most of the best "sprinters" in this study had participated in sprint skiing events and could profit from their previous training in sprinting. Their training data and self-reported sprint ability might suggest that long-distance skiers' training routines have an unused potential to further develop their speed systematically.

Methodological Considerations

The strength of this study is the high number of top-level long-distance XC skiers providing novel data on training associated with success in this sport. However, the study also has some limitations: (1) recall bias is a limitation of retrospective questionnaires; (2) we were unfortunately not able to recruit any female participants and thus to investigate potential sex differences and generalize the findings to the female population; and (3) as the authors used their own network in the recruitment process, potential selection bias such as including only Norwegian and Swedish skiers may have affected the findings.

CONCLUSIONS

The training of world-class long-distance XC skiers consists of high volumes (i.e., 861 ± 90 h annually) where low-intensity endurance training predominates. More specifically, long-distance skiers perform relatively long but few sessions (i.e., regular 3- to 5-h sessions), use a pyramidal intensity distribution pattern (i.e., 88.7% LIT, 6.4% MIT, and 4.8% HIT), and spend much (50–60%) of their training time using the DP technique. In addition, competition-specific sessions, such as long-duration LIT-to-MIT finalized with HIT or sprint training, are specific features of the training of long-distance XC skiers. Accordingly, the training routines seem to match the specific demands of long-distance XC skiing, with competitions commonly performed as long-duration DP. The week-to-week periodization included relatively evenly distributed training loads in GP and SP. However, all skiers had a pronounced periodization pattern during CP, where high-volume training weeks were followed by competition weeks with half of the training load and less strain on the upper body to ensure muscular fitness for the competitions.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for studies of this type. Therefore, the ethics of the study were according to the institutional requirements, while approval for data security and handling was obtained from the

Norwegian Center for Research Data. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

P-ØT and ØS planed and designed the study. P-ØT and GS performed the data collection. P-ØT, GS, and ØS analyzed and presented the data, authored and finalized the manuscript for publication, and have approved the final manuscript. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

We would like to thank the skiers for their participation, enthusiasm and cooperation in this study.

REFERENCES

Calbet, J. A., Holmberg, H. C., Rosdahl, H., van Hall, G., Jensen-Urstad, M., and Saltin, B. (2005). Why do arms extract less oxygen than legs during exercise? *Am. J. Physiol.-Regul. Integr. Comp. Physiol.* 289, R1448–R1458.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioural Sciences.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Faria, E. W., Parker, D. L., and Faria, I. E. (2005). The science of cycling. *Sports Med.* 35, 285–312. doi: 10.2165/00007256-200535040-00002

Holmberg, H.-C. (2015). The elite cross-country skier provides unique insights into human exercise physiology. *Scand. J. Med. Sci. Sports* 25:100. doi: 10.1111/sms.12601

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *J. Sports Med. Phys. Fitness* 48, 65–75.

Knechtle, B., and Nikolaidis, P. T. (2018). Physiology and pathophysiology in ultra-marathon running. *Front. Physiol.* 9:634. doi: 10.3389/fphys.2018.00634

Laursen, P. B. (2010). Training for intense exercise performance: high-intensity or high-volume training? *Scand. J. Med. Sci. Sports* 20 (Suppl. 2), 1–10. doi: 10.1111/j.1600-0838.2010.01184.x

Losnegard, T., and Hallén, J. (2014). Physiological differences between sprint- and distance-specialized cross-country skiers. *Int. J. Sports Physiol. Perform* 9, 25–31. doi: 10.1123/ijspp.2013-0066

Matwejew, L. (1975). *Periodisierung des sportlichen trainings.* Berlin: Bartels & Wernitz.

Rasdal, V., Moen, F., and Sandbakk, Ø. (2018). The long-term development of training, technical, and physiological characteristics of an olympic champion in nordic combined. *Front. Physiol.* 9:931. doi: 10.3389/fphys.2018.00931

Sagelv, E. H., Engseth, T. P., Pedersen, S., Pettersen, S. A., Mathisen, G., Heitmann, K. A., et al. (2018). Physiological comparisons of elite male visma ski classics and national level cross-country skiers during uphill treadmill roller skiing. *Front. Physiol.* 9:1523. doi: 10.3389/fphys.2018.01523

Sandbakk, Ø. (2018). Praktical implementation of strength training to improve the performance of world-class cross-country skiers. *Kinesiolgy* 50, 1–8.

Sandbakk, Ø., Hegge, A. M., Losnegard, T., Skattebo, O., Tonnessen, E., and Holmberg, H. C. (2016). The physiological capacity of the world's highest ranked female cross-country skiers. *Med. Sci. Sports Exerc.* 48, 1091–1100. doi: 10.1249/MSS.0000000000000862

Sandbakk, Ø., and Holmberg, H.-C. (2017). Physiological capacity and training routines of elite cross-country skiers: approaching the upper limits of human endurance. *Int. J. Sports Physiol. Perform* 12, 1003–1011. doi: 10.1123/ijspp.2016-0749

Sandbakk, Ø., and Holmberg, H. C. (2014). A reappraisal of success factors for olympic cross-country skiing. *Int. J. Sports Physiol. Perform.* 9, 117–121.

Sandbakk, Ø., Holmberg, H. C., Leirdal, S., and Ettema, G. (2011). The physiology of world-class sprint skiers. *Scand. J. Med. Sci. Sports* 21, e9–e16. doi: 10.1111/j.1600-0838.2010.01117.x

Seiler, K. S., and Kjerland, G. O. (2006). Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? *Scand. J. Med. Sci. Sports* 16, 49–56. doi: 10.1111/j.1600-0838.2004.00418.x

Skattebo, Ø., Losnegard, T., and Stadheim, H. K. (2019). Double poling physiology and kinematics of elite cross-country skiers: specialized long-distance versus all-round skiers. *Int. J. Sports Physiol. Perform* 14, 1190–1199. doi: 10.1123/ijspp.2018-0471

Solli, G. S., Kocbach, J., Bucher Sandbakk, S., Haugnes, P., Losnegard, T., and Sandbakk, Ø. (2020). Sex-based differences in sub-technique selection during an international classical cross-country skiing competition. *PLoS ONE* 15:e0239862. doi: 10.1371/journal.pone.0239862

Solli, G. S., Kocbach, J., Seeberg, T. M., Tjonnas, J., Rindal, O. M. H., Haugnes, P., et al. (2018). Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *PLoS ONE* 13, e0207195. doi: 10.1371/journal.pone.0207195

Solli, G. S., Tønnessen, E., and Sandbakk, Ø. (2017). The training characteristics of the world's most successful female cross-country skier. *Front. Physiol.* 8:1069. doi: 10.3389/fphys.2017.01069

Solli, G. S., Tønnessen, E., and Sandbakk, Ø. (2019). Block vs. traditional periodization of HIT: two different paths to success for the world's best cross-country skier. *Front. Physiol.* 10:375. doi: 10.3389/fphys.2019.00375

Stöggl, T. L., Hertlein, M., Brunauer, R., Welde, B., Andersson, E. P., and Swaren, M. (2020). Pacing, exercise intensity, and technique by performance level in long-distance cross-country skiing. *Front. Physiol.* 11:17. doi: 10.3389/fphys.2020.00017

Stöggl, T. L., and Sperlich, B. (2015). The training intensity distribution among well-trained and elite endurance athletes. *Front. Physiol.* 6:295. doi: 10.3389/fphys.2015.00295

Sylta, Ø., Tønnessen, E., and Seiler, S. (2014). From heart-rate data to training quantification: a comparison of 3 methods of training-intensity analysis. *Int. J. Sports Physiol. Perform.* 9, 100–107. doi: 10.1123/ijspp.2013-0298

Tønnessen, E., Svendsen, I. S., Rønnestad, B. R., Hisdal, J., Haugen, T. A., and Seiler, S. (2015). The annual training periodization of 8 world champions in orienteering. *Int. J. Sports Physiol. Perform* 10, 29–38. doi: 10.1123/ijspp.2014-0005

Tønnessen, E., Sylta, Ø., Haugen, T. A., Hem, E., Svendsen, I. S., and Seiler, S. (2014). The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance. *PLoS ONE* 9:e101796. doi: 10.1371/journal.pone.0101796

Zoppirolli, C., Bortolan, L., Schena, F., and Pellegrini, B. (2020). Double poling kinematic changes during the course of a long-distance race: effect of performance level. *J. Sports Sci.* 38, 863–872. doi: 10.1080/02640414.2020.1736246

Zoppirolli, C., Bortolan, L., Stella, F., Boccia, G., Holmberg, H.-C., Schena, F., et al. (2018). Following a long-distance classical race the whole-body kinematics of double poling by elite cross-country skiers are altered. *Front. Physiol.* 9:978. doi: 10.3389/fphys.2018.00978

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.

Study III

Journal of Human Kinetics volume 77/2021, 97-105 DOI: 10.2478/hukin-2021-0014
Section II - Exercise Physiology & Sports Medicine

The Effects of Sub-Technique and Pole Length on Classic Roller Skiing Performance and Physiological Responses at Steep Uphill Inclination

by

Per-Øyvind Torvik[1], *Johan Persson*[1], *Roland van den Tillaar*[2]

The aims of this study were to compare performance with physiological and perceptual responses on steep uphill inclines between double poling and diagonal stride and to investigate the effects of pole length when double poling. Eight male, competitive cross-country skiers (22 ± 1.1 yrs, peak oxygen uptake (VO_{2peak}) in the diagonal stride: 69.4 ± 5.5 $ml\cdot kg^{-1}\cdot min^{-1}$) performed four identical tests, one in the diagonal stride, and three in double poling with different pole lengths (self-selected, self-selected -5 cm and self-selected +10 cm). Each test was conducted at a fixed speed (10 km/h), with inclination rising by 1%, starting with 7%, each until voluntary exhaustion. VO_{2peak}, the heart rate, blood lactate concentration, and the rating of perceived exertion were determined for each pole length in each test. The peak heart rate ($p < 0.001$) and VO_{2peak} ($p = 0.004$) were significantly higher in the diagonal stride test compared with double poling with all pole lengths. Time to exhaustion (TTE) differed significantly between all four conditions (all $p < 0.001$), with the following order from the shortest to the longest TTE: short poles, normal poles and long poles in double poling, and the diagonal stride. Consequently, a significantly higher slope inclination was reached ($p < 0.001$) using the diagonal stride (17%) than for double poling with long poles (14%), normal (13%) and short (13%) poles. The current study showed better performance and higher VO_{2peak} in the diagonal stride compared to double poling in steep uphill terrain, demonstrating the superiority of the diagonal stride for uphill skiing. However, in double poling, skiers achieved improved performance due to greater skiing efficiency when using long poles, compared to normal and short poles.

Key words: *cross-country skiing, peak oxygen uptake, incremental test, XC skiing.*

Introduction

In recent years, double poling has become the predominant sub-technique in classic cross-country skiing. Traditionally, the advantages of using double poling have been most pronounced in flat and downhill terrains, although double poling is used even in steep uphill terrain (Welde et al., 2017) where the diagonal stride is normally regarded as more efficient (Stöggl and Holmberg, 2011). However, studies (Dahl et al., 2017; Pellegrini et al., 2011) have shown that on uphill gradients steeper than 8-9% skiers prefer diagonal stride to double poling technique.

Since all propulsion in double poling is generated through the poles, a key question is whether pole length would influence performance and physiological aspects. Recent studies examining this topic (Carlsen et al., 2018; Losnegard et al., 2017b; Onasch et al., 2017) showed that in low and moderate uphill terrains, double poling with longer poles resulted in reduced vertical displacement of the centre of mass (CoM), longer poling time when going uphill, and lower oxygen cost at a standard work load. In addition, an earlier study (Hoffman et al., 1994) showed lower oxygen cost in double poling

---

[1] - *Department of Sports Sciences and Physical Education, Nord University, Meråker, Norway.*
[2] - *Department of Sports Sciences and Physical Education, Nord University, Levanger, Norway.*

Authors submitted their contribution to the article to the editorial board.
Accepted for printing in the Journal of Human Kinetics vol. 77/2021 in January 2021.

with longer poles (89% vs. 83% of body length) in flat terrain, while Nilsen et al. (2003) described the advantages of long poles with longer poling time and more horizontally directed ground reaction forces. Hansen and Losnegard (2010) investigated long (>7.5 cm) and short (<7.5 cm) poles with self-preferred pole length in flat terrain and concluded that propulsion speed was higher with longer poles than with self-preferred. Further exploration of differences between pole length in steep uphill terrain showed that the effect of incline on this relationship and differences with the diagonal stride might provide important information for athletes and coaches, as well as for policy makers wishing to keep the classic diagonal stride as a competition style. The International Ski Federation (FIS) introduced new rules in 2016 concerning pole length and technique in classic competitions, where pole length was limited to 83% of the athlete's body height measured with ski boots on (FIS § ICR 348.8.1). In 2018, the FIS also included zones in the tracks where only the diagonal stride technique was permitted. Despite these restrictions, some athletes have still been able to successfully execute some races without kick wax and using mainly double poling, simulating the diagonal stride and using the herringbone technique in the technique zones.

Pole length is one of the crucial components influencing propulsion in double poling (Losnegard et al., 2017b; Stöggl and Holmberg, 2011). Beside pole length, several other key components have also contributed to the increased current use of double poling in cross-country skiing. Firstly, speed in classic cross-country skiing has increased due to athletes having stronger and better endurance-trained upper bodies (Stöggl et al., 2011), improved equipment and track preparation (Sandbakk and Holmberg, 2014; Stöggl and Holmberg, 2011) and better ski preparation along with pole quality (Stöggl and Holmberg, 2011). Secondly, a more effective double poling technique has emerged (Holmberg et al., 2005), with associated improvement in a) the sequential movement pattern in the hip, shoulder, and elbow joints (Komi and Norman, 1987; Lindinger et al., 2009), b) the forward orientation of the body, c) the orientation of the pole plant (Stöggl et al., 2011), d) the timing of pole force (Stöggl et al., 2011), e) characteristics of the repositioning of the whole body into the next stroke (Stöggl et al., 2011), and f) reduced vertical displacement range of the CoM (Carlsen et al., 2018; Losnegard et al., 2017b). All these changes in the kinematic and force components caused longer cycle lengths in the fastest skiers on flat and uphill terrain compared to slower skiers (Lindinger et al., 2009; Losnegard et al., 2017b; Stöggl and Holmberg, 2011, 2016; Stöggl et al., 2011) and they may be reinforced by longer poles.

To our knowledge, no study has investigated the effect of different pole lengths in steep uphill terrain on performance, physiological and perceptual responses to double poling, and quantified the differences in these variables compared to the diagonal stride in such terrain. Therefore, the aims of this study were to compare performance and physiological responses on steep uphill inclines between double poling and the diagonal stride and to investigate the effects of pole length when double poling.

Methods

Characteristics of the participants

Eight elite male cross-country skiers (age: 22 ± 1.1 years; body mass: 77.1 ± 5.0 kg; body height: 183 ± 3.6 cm), competing at the national level with an average of 120 ± 44 FIS points and maximal oxygen uptake (VO_{2max}) in the diagonal stride of 69.4 ± 5.1 $ml \cdot min^{-1} \cdot kg^{-1}$, participated voluntarily in the study. They were fully informed about the content of the study before giving written informed consent to participate. The study was approved by the Norwegian Centre for Research Data and conducted in accordance with current ethical standards in sports and exercise research.

Experimental design and procedures

To investigate the physiological and perceptual responses to different pole lengths and propulsion techniques in different slope inclinations, a counterbalanced crossover design with repeated measures was used. Each participant was tested under four conditions: 1) diagonal stride with normal poles (~83% of body height), 2) double poling with short poles (~80% of body height), 3) double poling with self-selected pole lengths, and 4) double poling with long poles (~88% of body height). Two tests took place on one day and two on the following day. The order of the four conditions was randomized for each participant, to avoid an order and fatigue effect. Since there were two maximal tests per day, there was at least four hours of recovery between tests.

The tests on the first and second days were at the same time of day. A standardized warm-up procedure consisted of 10 min running at 60–70% of the maximum heart rate on a motor-driven treadmill (Rodby 2500ML, Södertalje, Sweden) designed for roller ski testing. Participants then changed to skiing equipment and performed five min warm-up roller skiing with the technique and pole length specific to each test on a motor-driven treadmill (Rodby 3500ML, Södertalje, Sweden) designed for roller skiing. To exclude variations in rolling resistance, all athletes used the same pair of roller skis (SWENOR Fiberglass roller, standard resistance wheel 2, Trøsken, Norway), with Rottefella performance classic bindings (Rottefella, Klokkarstua, Norway). The poles (Swix CT1, Lillehammer, Norway) had special carbide tips to prevent them from slipping on the treadmill belt. After the warm-up, participants had a one min rest interval before the actual test started.

Participants then performed, in randomized order, one of the four progressive uphill treadmill roller skiing tests: 1) in diagonal stride and 2-4) double poling with short, self-selected, and long poles, respectively. The pole lengths were selected based on previous studies (Hansen and Losnegard, 2010; Losnegard et al., 2017b). The short poles were 5 cm shorter (~80%) than the self-selected poles, which were 83±1% of body height. The longer poles were 10 cm longer (~88% of body height) than the self-selected poles. All tests were executed at 10 km/h, an average uphill competition speed (Larsson and Henriksson-Larsén, 2008). The test started at 7% uphill, increasing 1% each minute until exhaustion. Participants were secured with a safety harness hanging from the ceiling, connected to the safety stop system of the treadmill. Testing on a treadmill was chosen to achieve standardized conditions during the measurements. The starting inclination of 7% was chosen to avoid preliminary fatigue when starting at a lower inclination.

Measurements

Mean oxygen uptake was measured using an Oxycon Pro apparatus with a mixing chamber (Jaeger GmbH, Hoechberg) every 10 s and every minute of the test, while VO_2 was calculated by the average three values closest (last 30 s) to every step change. Peak oxygen uptake (VO_{2peak}) was accepted when two of the following three criteria were achieved: a respiratory exchange ratio above 1.10, blood lactate above 8 mmol·L^{-1} and a plateau in VO_2 with increasing exercise intensity (Holmberg et al., 2007). Before each test, VO_2 and VCO_2 gas analysers were calibrated using high-precision gases (15.00 ± 0.04% O_2 and 5.85 ± 0.1% CO_2, (CareFusion gas GmbH Höchberg, Germany). The flow meter was calibrated with a 3 L volume syringe (Hans Rudolph Inc., Kansas City, Missouri, USA). In addition, peak inclination on the treadmill was recorded for each test together with total time to exhaustion (TTE). The heart rate was measured with a heart rate monitor (Polar RC3GPS, Polar Electro OY, Kempele. Finland), using 5 s intervals for data storage. After each test, the LT-1710 Lactate Pro analyser (Arkray Factory Inc., KDK Corporation, Shiga, Japan) was used to measure blood lactate concentration from the fingertip of each participant. The athletes' ratings of perceived exertion (RPE), measured (6–20) on the Borg scale (Borg, 1982), were also recorded after each test.

Statistical analysis

To compare the effects of pole length and propulsion on different physiological and perceptual variables, a one-way ANOVA with repeated measures on each variable was performed. To compare the heart rate and oxygen uptake under the four conditions, a four x seven (slope inclination) multivariate ANOVA was conducted. Post-hoc comparisons with Holm-Bonferroni corrections were conducted to determine differences. When sphericity assumptions were violated, Greenhouse-Geisser adjustments of the p-values were reported.

The level of significance was set at $p < 0.05$ and all data were expressed as mean ± SD. Size effect was evaluated with η^2 (partial eta squared), where $0.01<\eta^2<0.06$ constituted a small effect, $0.06<\eta^2<0.14$ a medium effect, and $\eta^2>0.14$ a large effect (Cohen, 2013). Statistical analysis was performed in SPSS, Version 23.0 (SPSS Inc., Chicago, IL).

Results

No significant differences in the RPE ($F = 1.3$, $p = 0.30$, $\eta^2 = 0.16$) or lactate concentration

(F=0.87, p = 0.47 η^2 = 0.11) were found between the four conditions (Table 1).

The peak heart rate (F = 22.2, $p < 0.001$, η^2 = 0.76) and peak oxygen uptake (F = 6.1, p = 0.004, η^2 = 0.47) were significantly higher in the diagonal stride test compared with the three double poling conditions at complete exhaustion. In addition, TTE was significantly different between all four conditions (F = 135, $p < 0.001$, η^2 = 0.95), i.e. short, self-selected and long poles double poling and diagonal stride, in order from the shortest to the longest TTE (Table 1). This also implied a significantly higher slope inclination (F = 91, $p < 0.001$, η^2 = 0.93) for the diagonal stride (17%) compared to double poling with long (14%), self-selected (13%) and short (13%) poles (Figure 1).

When analysing alterations in the heart rate and oxygen uptake under the different conditions, a significant effect of condition (F = 189.6, $p < 0.001$, η^2 = 0.87) and an interaction effect (F = 8.3, $p < 0.001$, η^2 = 0.74) were found for oxygen uptake (Figure 1). For the heart rate only, a significant interaction effect (F = 1.8, p = 0.042, η^2 = 0.38, Figure 2) was found.

Table 1

Physiological and perceptual variables at complete exhaustion

Variable	Diagonal stride		Double poling	
		Shorter pole	Self-selected	Longer poles
Blood lactate (mmol/l)	10.4 ± 1.5	11.2 ± 1.9	10.4 ± 1.0	11.0 ± 1.8
RPE	18.8 ± 1.0	18.0 ± 0.8	18.5 ± 1.1	18.3 ± 1.0
Peak heart rate (beats/min)	191 ± 6*	184 ± 6	185 ± 6	184 ± 4
VO_{2peak} (ml/min/kg)	69.4 ± 5.5*	66.3 ± 5.7	65.3 ± 6.7	65.6 ± 6.4
Peak slope inclination (%)	17.3 ± 1.6*	13.1 ± 1.0	13.3 ± 1.0	14.1 ± 1.4*
Time to exhaustion (s)	637 ± 86*	382 ± 53*	402 ± 56*	444 ± 78*

** indicates a significant difference with the other three conditions on a $p < 0.05$ level.*
RPE: rating of perceived exertion. VO_{2peak}: Peak oxygen uptake

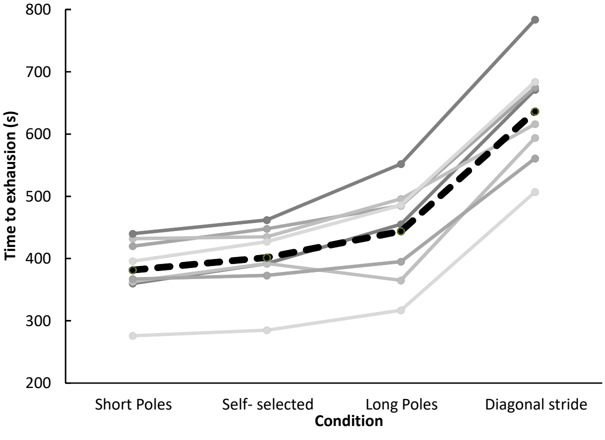


Figure 1

Individual time to exhaustion in each of the four skiing conditions and average over all participants (- - -)

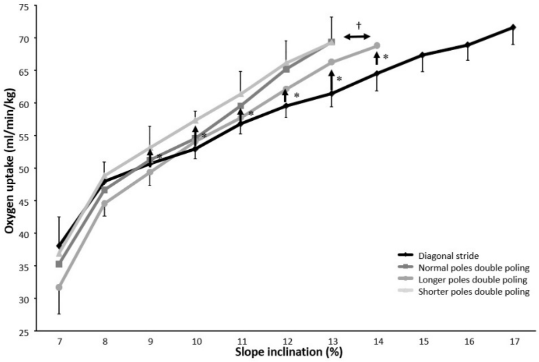


Figure 2

Mean oxygen uptake at the different slope inclinations for each of the skiing conditions
** indicates a significant difference between diagonal stride and the other conditions on the specified incline on a p < 0.05 level. † indicates a significant difference at all inclinations between double poling with long poles and short poles on a p < 0.05 level.*

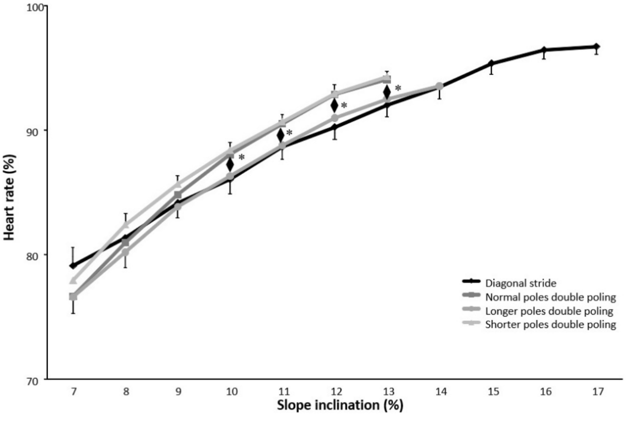


Figure 3

Mean heart rate at the different slope inclinations averaged per ***condition***
** indicates a significant difference between diagonal stride and double poling with long poles compared to double poling with normal and shorter poles on the specified inclines on a p < 0.05 level.*

Post-hoc comparison revealed lower oxygen uptake for double poling with long compared to short poles at all inclinations (range 5.0-3.25 ml·min^{-1}·kg^{-1} from 7-13%), while oxygen uptake was lower for the diagonal stride than for double poling with short poles on inclines steeper than 9% (0.9-7.86 ml·min^{-1}·kg^{-1} from 8-13%). From 10% inclination, oxygen uptake was also lower in the diagonal stride compared to the self-selected and short poles, while from 12%, oxygen uptake was also lower than with double poling with long poles (range 2.60-4.25 ml·min^{-1}·kg^{-1} from 12-14%; Figure 2). Furthermore, from 10% inclination, the heart rate was significantly ($p > 0.019$-0.051) lower during the diagonal stride and double poling with long poles compared to the other two double poling conditions (Figure 3).

Discussion

This study compared performance and physiological responses on steep uphill inclines between double poling and the diagonal stride and investigated the effects of pole length when double poling. The two main findings were as follows: 1) the diagonal stride showed significantly longer TTE (i.e. improved roller ski performance) when roller skiing on steep uphill terrain than double poling independent of pole length. This difference coincided with lower submaximal oxygen cost (indicating better skiing efficiency) at all inclinations above 10%, but higher VO_{2peak} compared to the values reached in double poling; 2) increasing pole length gradually increased TTE and thereby the ability to double pole on steep inclines. This was reflected in lower submaximal oxygen cost for long versus self-selected and short poles, without any difference in the peak heart rate and peak oxygen uptake across double poling conditions.

The current study showed longer TTE in the diagonal stride XC skiing technique than double poling independent of pole length when roller skiing on steep uphill terrain. This difference coincided with lower oxygen uptake (indicating better skiing efficiency) with the diagonal stride at all inclinations above 10%, in combination with higher peak oxygen uptake compared to the values reached in double poling. These results were as expected in comparison with previous studies, where e.g. Dahl et al. (2017) showed clearly better skiing efficiency with the diagonal stride compared to double poling on inclines above 12% when roller skiing. Holmberg et al. (2007) showed gradually increasing VO_{2peak} with a higher muscle mass involved from arm cranking to the diagonal stride (i.e. whole-body work). The clear increase in VO_{2peak} in the diagonal stride compared to double poling found in our study indicates that double poling does not produce enough power to tax the cardiovascular system maximally (Undebakke et al., 2019) and thereby also limits performance in steep uphills where the diagonal stride can be used optimally. Overall our study provides novel data on the superiority of the diagonal stride technique for uphill performance and supports previous studies that have found that this is due to both greater energy delivery capacity and better efficiency.

In the diagonal stride, one or both limbs always produce propulsive force throughout the cycle, which is not the case for double poling where the short propulsion and long recovery times are less effective in steep uphills; here, considerable power is exerted against gravity. However, the roller ski brake reduces the need for vertical force to prevent the skis from slipping when executing the classic kick on roller skis, which is likely to induce more efficient forward propulsion than when skiing on snow. While this might reduce the difference between diagonal and double poling performance during on-snow skiing, it seems logical that the above-mentioned mechanisms make the diagonal stride more effective than double poling on steep uphill terrain also when skiing on snow. However, double poling on snow may outperform the diagonal stride on uphill terrain under difficult waxing and skiing conditions, and even though the diagonal stride is effective in steep parts of the track, skis without grip wax glide better and make double poling faster in downhills, flat terrain and curves in a competition track.

Although the diagonal stride seems superior in steeper uphills, double poling is a more efficient technique in other parts of the tracks and might be exclusively used in some races. In such cases, evaluation of pole length for performance in both flat and uphill double poling should be considered. This was reflected in lower submaximal oxygen cost for long versus self-selected and short poles, without any difference in peak energy delivery capacity across double poling conditions. While longer poles have been shown to be more effective in flat terrain, slight uphills and varied terrain (Hoffman et al., 1990; Onasch et al., 2017; Losnegard et al., 2017b; Carlsen et al., 2018), this is the first study to examine longer poles in steep uphills, indicating that they improve performance by enhancing skiing efficiency also in steep terrain.

The longer TTE achieved by double poling with long poles concurs with the findings of Losnegard et al. (2017b) who reported better performance (time trial) and lower oxygen costs with long poles at flat and moderate uphills. The novel findings of our study are the advantage of long poles (i.e. lower oxygen cost and heart rate) compared to the self-selected and short poles, and that this is apparent at 7-8% inclination and upward. This is of great interest in cases where this technique is exclusively used in competitions. The gap in energy cost increases between short/self-selected poles, compared to long poles with inclinations greater than 8%. The positive effect of long poles with increasing uphill inclination agrees with earlier investigations (Carlsen et al., 2018), but this has previously only been shown up to 7.9% inclination (Onasch et al., 2017).

The difference in oxygen cost with long poles versus short and self-selected poles might be explained by the longer propulsion cycle with long poles (Onasch et al., 2017), and thus more propulsion executed per cycle with the same or reduced vertical CoM displacement (Carlsen et al., 2018). In contrast, shorter poles in double poling are associated with higher poling frequency and reduced propulsive power per poling cycle (Onasch et al., 2017). Longer poles are also reported to have several kinematic advantages such as a more upright working posture, reduced vertical displacement of the CoM and more effective use of uphill (Carlsen et al., 2018). Although displacement of the CoM and range of motion (RoM) were not measured here, which must be considered a shortcoming of this study, several other studies have pointed out that less vertical displacement of the CoM in uphill skiing with longer poles has a positive influence on oxygen cost (Carlsen et al., 2018; Losnegard et al., 2017b). Consequently, these factors result in higher oxygen cost with short and self-selected poles compared to long poles.

Conclusion

The diagonal stride on roller skis showed significantly improved performance on steep uphill terrain compared to double poling independent of pole length, demonstrating the superiority of the diagonal stride technique in such terrain. This difference coincided with lower submaximal oxygen cost at all inclinations above 10%, which indicates better skiing efficiency, as well as higher peak oxygen uptake than that achieved in double poling. Hence, the diagonal stride seems to be superior to double poling on steep uphills due to both greater energy delivery capacity and better efficiency. Although VO_{2peak} was the same with all pole lengths, longer poles showed a lower heart rate and oxygen cost on comparable submaximal inclines, indicating that longer poles improve performance by enhancing skiing efficiency. This study shows that increasing pole length gradually increased performance and thereby the ability to double pole on steep inclines. Therefore, future experimental studies should analyse the effectiveness of different sub-techniques throughout entire race-tracks and include biomechanical analyses to further understand the underlying mechanisms.

References

Borg AVG. Psychophysical bases of perceived exertion. *Med Sci Sport Exer,* 1982; 14(5): 377-381. doi:10.1249/00005768-198205000-00012

Carlsen CH, Rud B, Myklebust H, Losnegard T. Pole lengths influence O2-cost during double poling in highly trained cross-country skiers. *Eur J Appl Physiol,* 2018; 118(2): 271-281. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5767204/pdf/421_2017_Article_3767.pdf. doi:10.1007/s00421-017-3767-x

Cohen J. *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.): Routledge Ltd.; 2013

Dahl C, Sandbakk Ø, Danielsen J, Ettema G. The Role of Power Fluctuations in the Preference of Diagonal vs. Double Poling Sub-Technique at Different Incline-Speed Combinations in Elite Cross-Country Skiers. *Front Physiol,* 2017; 8(94): 1-9. doi:10.3389/fphys.2017.00094

Hansen E, Losnegard T. Pole length affects cross-country skiers' performance in an 80-m double poling trial performed on snow from standing start. *Sports Engin,* 2010; 12(4): 171-178. Retrieved from https://link.springer.com/content/pdf/10.1007%2Fs12283-010-0042-3.pdf. doi:10.1007/s12283-010-0042-3

Hoffman DM, Clifford SP. Physiological responses to different cross country skiing techniques on level terrain. *Med Sci Sport Exer,* 1990; 22(6): 841-848. doi:10.1249/00005768-199012000-00017

Hoffman DM, Clifford SP, Watts BP, Drobish MK, Gibbons PT, Newbury SV, O'Hagan PK. Physiological comparison of uphill roller skiing: diagonal stride versus double pole. *Med Sci Sport Exer,* 1994; 26(10): 1284-1289. doi:10.1249/00005768-199410000-00017

Holmberg HC, Lindinger S, Stöggl T, Eitzlmair E, Muller E. Biomechanical analysis of double poling in elite cross-country skiers. *Med Sci Sport Exer,* 2005; 37(5): 807-818. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/15870635.

Holmberg HC, Rosdahl H, Svedenhag J. Lung function, arterial saturation and oxygen uptake in elite cross country skiers: influence of exercise mode. *Scand J Med Sci Sport, 2007;* 17(4): 437-444. Retrieved from https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1600-0838.2006.00592.x. doi:10.1111/j.1600-0838.2006.00592.x

Komi PV, Norman RW. Preloading of the thrust phase in cross-country skiing. *Int J Sport Med,* 1987; 8(1): 48-54

Larsson P, Henriksson-Larsén K. Body Composition and Performance in Cross-Country Skiing. *Int J Sports Med,* 2008; 29(12): 971-975. Retrieved from https://www.thieme-connect.com/products/ejournals/abstract/10.1055/s-2008-1038735. doi:10.1055/s-2008-1038735

Lindinger S, Holmberg HC, Müller E, Rapp W. Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing. *Eur J Appl Physiol,* 2009; 106(3): 353-363. Retrieved from https://link.springer.com/content/pdf/10.1007%2Fs00421-009-1018-5.pdf. doi:10.1007/s00421-009-1018-5

Losnegard T, Myklebust H, Skattebo O, Stadheim HK, Sandbakk J, Hallén J. The influence of pole length on performance, O2 cost, and kinematics in double poling. *Int J Sport Physiol,* 2017b; 12(2): 211-217. doi:10.1123/ijspp.2015-0754

Onasch, F, Killick A, Herzog W. Is there an optimal pole length for double poling in cross country skiing? *J Appl Biomech,* 2017; 33(3): 197-202. doi:10.1123/jab.2016-0071

Pellegrini B, Bortolan L, Schena F. Poling force analysis in diagonal stride at different grades in cross country skiers. *Scand J Med Sci Sport,* 2011; 21(4): 589. Retrieved from https://www.tandfonline.com/doi/pdf/10.1080/17461391.2016.1249031?needAccess=true. doi:10.1111/j.1600-0838.2009.01071.x

Sandbakk Ø, Holmberg HC. A Reappraisal of Success Factors for Olympic Cross-Country Skiing. *Int J Sport Physiol,* 2014; 9(1): 117-121. doi:10.1123/IJSPP.2013-0373

Stöggl LT, Holmberg HC. Force interaction and 3D pole movement in double poling. *Scand J Med Sci Sport,* 2011; 21(6): e393-e404. Retrieved from https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1600-0838.2011.01324.x. doi:10.1111/j.1600-0838.2011.01324.x

Stöggl LT, Holmberg HC. Double-Poling Biomechanics of Elite Cross-country Skiers: Flat versus Uphill Terrain. *Med Sci Sport Exerc,* 2016; 48(8): 1580-1589. doi:10.1249/MSS.0000000000000943

Stöggl LT, Müller E, Ainegren M, Holmberg HC. General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand J Med Sci Sport,* 2011; 21(6): 791-803. Retrieved from https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1600-0838.2009.01078.x. doi:10.1111/j.1600-0838.2009.01078.x

Undebakke V, Berg J, Tjønna AE, Sandbakk Ø. Comparison of Physiological and Perceptual Responses to Upper-, Lower-, and Whole-Body Exercise in Elite Cross-Country Skiers. *J Strength Cond Res,* 2019; 33(4): 1897-1177. doi:10.1519/JSC.0000000000003078

Welde B, Stöggl TL, Mathisen GE, Supej M, Zoppirolli C, Winther AK, Holmberg HC. 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): Retrieved from https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0187111&type=printable. doi:10.1371/journal.pone.0187111

Zoppirolli C, Pellegrini B, Bortolan L, Schena F. Energetics and biomechanics of double poling in regional and high-level cross-country skiers. *Eur J Appl Physiol,* 2015; 115(5): 969. Retrieved from https://link.springer.com/content/pdf/10.1007%2Fs00421-014-3078-4.pdf. doi:10.1007/s00421-014-3078-4

Corresponding author:

Per-Øyvind Torvik
Department of Sports Sciences and Physical Education,
Nord University, Levanger.
7530 Meråker Norway.
Phone: +47 74022984
Fax: +47 74112001
E-mail: per.o.torvik@nord.no

Study IV

RESEARCH ARTICLE

The effect of pole length on physiological and perceptual responses during G3 roller ski skating on uphill terrain

Per-Øyvind Torvik[1]*, **Erna Dianne von Heimburg**[1], **Torkel Sende**[1], **Boye Welde**[2]

1 Department of Sports Sciences and Physical Education, Nord University, Levanger, Norway, **2** UiT The Arctic University of Norway, School of Sport Sciences, Tromsø, Norway

* per.o.torvik@nord.no

Abstract

The benefits of using longer than self-selected poles have been shown in double poling, but these potential benefits have not been examined in the gear 3 ski skating sub-technique (G3), during which the poling movement is very similar to double poling. The aim of this study was to examine the effect of longer than self-selected poles on physiological and perceptual responses in the G3 sub-technique. Ten cross-country skiers and biathletes (VO_{2max} 72.4 ± 3.0 $ml{\cdot}min^{-1}{\cdot}kg^{-1}$, age 20.1 ± 2.8 years, height 1.81 ± 0.03 m and weight 73.1 ± 4.6 kg) completed two tests, each with three different submaximal intensities, during roller skiing using the G3 technique. The first test was carried out at a fixed speed (10 $km{\cdot}h^{-1}$) and the skiers performed two intervals of 5 min at 7, 9 and 11% inclination on a roller ski treadmill with self-selected poles (SSP) and 7.5 cm longer poles (LP) at each step. The second test had a fixed inclination of 4% and speeds of 14, 17 and 20 $km{\cdot}h^{-1}$, also performed with SSP and LP at each step. At fixed speed, the oxygen uptake was 2.7% lower ($P = 0.005$) and the gross efficiency (GE) 2.1% higher ($P = 0.01$) with LP than with SSP at the steepest inclination of 11%. At fixed inclination, the oxygen uptake was 2.1% lower ($P = 0.01$) and the GE was 4.1% higher ($P = 0.03$) with LP than with SSP at the highest speed of 20 $km{\cdot}h^{-1}$. At 14 $km{\cdot}h^{-1}$, the oxygen uptake was 3.0% lower ($P = 0.05$) and GE was 3.8% higher ($P = 0.03$) with LP than with SSP. Our novel findings show that longer poles in the G3 technique may enhance the efficiency of skiing.

Citation: Torvik P-y, Heimburg EDv, Sende T, Welde B (2019) The effect of pole length on physiological and perceptual responses during G3 roller ski skating on uphill terrain. PLoS ONE 14(2): e0211550. https://doi.org/10.1371/journal.pone.0211550

Editor: Luca Paolo Ardigò, Universita degli Studi di Verona, ITALY

Received: May 30, 2018

Accepted: January 16, 2019

Published: February 22, 2019

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Introduction

Effectively utilising metabolic energy to produce high speed is a crucial factor for endurance performance in sports like cross-country (XC) skiing [1]. The constant change in workload in XC skiing due to varying track conditions (changing snow and weather conditions) and track profiles consisting of different types of terrain (flat, uphill, downhill) challenge athletes with respect to the use of different sub-techniques and types of muscle use that require major adaptability of the cardiovascular system [1]. The speed and technique on the uphills is of particular interest since ~50% of race time is spent there [2, 3], and the main time differences between skiers have been reported to occur during uphill skiing [4, 5].

In the 1980s, XC skiing went through a technique revolution with the development of the skating style and five different ski skating sub-techniques are currently identified and used as a functional gear system during training and competitions [2, 6, 7]. Already in the very beginning of the world cup ski skating races, in 1985, longer poles than in classic style (~7.5–10 cm) were found beneficial [8]. The gear 3(G3) ski skating sub-technique is traditionally used at a high speed and is a symmetric sub-technique with one parallel pole plant with each skating stroke, one on each side [6]. The similarity in upper body work between double poling (DP) and G3 [9, 10] forms the basis for the claim that these two sub-techniques are limited by almost the same factors, at least when considering the work of the upper body muscles. The similarities between G3 and DP are shown in the way potential energy is gained between pole plants, the propulsive force in the poling action, and the conformity in upper-body muscle work [9].

Previous research has shown the beneficial effects of using longer poles (self-selected + 5–10 cm) in DP [7, 11, 12, 13, 14]. During DP, the force is transferred to the ground via the poles, and pole length seems to have a crucial influence on VO_2-cost and performance during DP in classic skiing [11]. The missing information about the effect of longer poles in skating necessitate a comparison with results of DP. Longer poles in DP enable higher speeds both in flat and level terrain [11] and there might be an inverted U-shape relationship between pole length and performance [13]. Several DP studies [11, 12] have pointed out the reduced vertical displacement of the body centre of mass (COM) while using longer poles as one important factor for lowered VO_2-cost and improved performance. The reduced VO_2-cost and improved performance with longer poles is also explained by the longer poling time and the effectiveness of slower muscle contraction [11]. Longer poles in DP lead to a more upright working position, reduced distance between COM and the poles, a pole plant further behind which provides a better working posture and a reduced VO_2-cost at the same workload [12]. Further, longer poles produce greater propulsive force, allow the skier to use the upper body and body mass more effectively [12,15] and, as pointed out by Carlsen and colleagues [12], longer poles and an upright posture will reduce the total range of motion on steeper terrain.

Despite the beneficial effects observed in the use of longer poles in DP, and the fact that skiers in skating are allowed to use poles as long as their body height (FIS§343.8.2), the potential benefit of longer poles in skating has not been fully explored. Therefore, the main aim of this study was to investigate the effect of pole length on physiological and perceptual responses caused by increasing speed and inclination during submaximal G3 roller skiing. It was hypothesised that longer poles have lower VO_2-cost and higher skating efficiency during submaximal G3 uphill treadmill roller skiing when workloads were altered either by inclination or by speed.

Materials and methods

Participants

Ten highly-trained, male junior skiers (six XC skiers and four biathlon skiers) with uphill treadmill running maximal oxygen uptake and heart rate (HR) of (mean ± SD) 72.4 ± 3.0 ml · min^{-1}· kg^{-1} and 196 ± 5 beats·min^{-1}, and age, height and body mass of 20.1 ± 2.8 years, 1.81 ± 0.03 m, and 73.1 ± 4.6 kg, respectively, volunteered to participate in this study. The participants were students at a Norwegian high school or a university with a special programme for XC skiing and biathlon. The participants had 147 ± 83 FIS points at the start of the study, and they had competed at the national level for 4 ± 2 years (range 2–8 years). They were familiar with treadmill roller skiing. The participants provided written informed consent to participate in the study, which was pre-approved by the Norwegian Centre for Research Data and the

Regional Ethics Committee in Trondheim, Norway, according to the Declaration of Helsinki. All participants were 18 years or older at the start of the study.

Design

To study the effect of self-selected pole length (SSP) and longer pole length (LP) (SSP+7.5 cm) on physiological and perceptual responses in the G3 technique during uphill treadmill roller skiing, two submaximal incremental tests with fixed speed or fixed inclination using a cross-over design were implemented. To determine submaximal intensity at each step of the two submaximal protocols, a peak oxygen uptake (VO_{2peak}) test in the G3 technique was carried out 2–7 days before the submaximal tests. A pilot study was conducted to determine inclination and speed for the two submaximal protocols, according to the intensity zones for endurance training established by the Norwegian Olympic Sports Centre (Olympiatoppen) [16]. The three lowest intensity zones for endurance training were established individually for each skier to be used as submaximal intensities in this study, namely $< 65\%$ (zone 1), 65–79% (zone 2) and 80–87% (zone 3) of the subjects' skating VO_{2peak}. Participants that measured values higher than 87% of their skating VO_{2peak} during the submaximal protocols were excluded from the analyses; one participant was excluded at VO_2 and GE from the submaximal protocol with fixed inclination as this test could not be considered submaximal (the subject reached 95% of his VO_{2peak} during the protocol).

Procedure

The participants prepared for the tests according to the instructions described earlier [17]. This meant that each participant arrived in the laboratory at the same time of day for all tests (G3 VO_{2peak}, submaximal incremental test with fixed speed, submaximal incremental test with fixed inclination). Over the 24 hours preceding the first test, each participant was instructed to eat his normal diet for preparing for a sprint competition, and the subjects replicated this diet before the second and third tests. Subjects arrived for testing in a rested and hydrated state, at least 2 hours postprandial and had avoided strenuous exercise, caffeine and alcohol in the 24 hours preceding the test sessions. Supplementation during the tests was restricted to 500 mL of a sports drink (Powerade). The VO_{2peak} test was performed on a 4% inclined treadmill, and the speed was increased incrementally each minute by 2 $km \cdot h^{-1}$ from 16 $km \cdot h^{-1}$ to exhaustion. The mean of the three highest 10-s consecutive VO_2 recordings at the end of the test was defined as VO_{2peak}. VO_{2peak} was accepted when two of the following three criteria were reached: a respiratory exchange ratio (RER) above 1.10, a blood lactate concentration above 8 $mmol \cdot L^{-1}$ and a plateau in VO_2 with increasing exercise intensity [18].

Each participant performed a standardised warm-up, consisting of 10 min running at 60–70% of maximum HR on a motor-driven treadmill. After the warm-up, participants had a one-minute rest before the actual test started. The participants then rollerskied on a skiing treadmill for five minutes using the G3 technique. To exclude variations in rolling resistance, all subjects used the same pair of roller skis. The poles were provided with special carbide tips to prevent them from slipping on the treadmill belt. The participants performed, in randomised order, two submaximal protocols of G3 skating. In the first protocol, treadmill inclines of 7, 9 and 11% were used at a constant speed of 10 $km \cdot h^{-1}$. In the second protocol, speeds of 14, 17 and 20 $km \cdot h^{-1}$ were used and the incline was constant at 4%. Each step contained 2 x 5 minutes with SSP and LP. There was a 1-minute recovery between each 5-minute step in order to measure blood lactate concentration, register perceptual response and change poles. The subjects either started with the SSP and ended with the LP (SSP-LP, LP-SSP, SSP-LP), or started with the LP and ended with the SSP (LP-SSP, SSP-LP, LP-SSP). SSP pole length was 89 ± 0.6%, and LP pole length was 94 ± 0.5%, of body height.

During each test, VO_2-uptake and HR were measured continuously. Furthermore, gross efficiency (GE) was calculated as external power divided by the total metabolic rate [19] and the formula for external power was calculated as the sum of power against gravity and friction:

$$\boldsymbol{External\ power} = \boldsymbol{m} \cdot \boldsymbol{g} \cdot \boldsymbol{v} \cdot [\boldsymbol{sin}(\boldsymbol{\alpha}) + \boldsymbol{cos}(\boldsymbol{\alpha}) \cdot (\mu)].$$

Here, m is the body mass, g the gravitational constant (9.81 $m \cdot s^{-2}$), v the treadmill speed, α the treadmill inclination and μ the frictional coefficient. The frictional coefficient was measured at 0.0237. Metabolic rate was calculated by using the $\dot{V}O_2$ and the associated respiratory exchange ratio (RER) from the last two minutes of each 5-minute interval together with the standard conversion tables [20].

Kinematic variables (cycle rate, cycle length) and knee angle were measured at the last step in each test (11% and 20 $km \cdot h^{-1}$). The last steps were chosen for kinematic and angle analyses because these workloads are considered to be closest to competition conditions. Participants were always secured with a safety harness hanging from the ceiling, connected to the safety brake system of the treadmill.

Instruments and measurements

The subjects skied on a treadmill (Rodby 3500ML, Södertalje, Sweden) using skating roller skis (SWENOR skate, standard resistance wheel 2, Trøsken, Norway) with Rottefella Performance skate bindings (Rottefella, Klokkarstua, Norway) and ski poles (Swix CT1, Lillehammer, Norway), and ran on a treadmill (Rodby 2500ML, Södertalje, Sweden).

Oxygen uptake was measured by an Oxycon Pro apparatus with a mixing chamber (Jaeger GmbH, Hochberg, Germany), using a 10-second interval for data storage. Before each test, the VO_2 and VCO_2 gas analysers were calibrated against both ambient air and a commercial mixture of high-precision gases (15.00 ± 0.04% VO_2 and 5.85 ± 0.1% VCO_2) (CareFusion gas GmbH, Hochberg, Germany) at the start of each test. The VO_2 and VCO_2 content of the ambient air was recorded and the flow meter was calibrated with a 3-L high-precision syringe (Hans Rudolph Inc., Kansas City, Missouri, USA). HR was measured with a heart rate monitor (Polar RC3GPS, Polar Electro OY, Kempele, Finland), using a five-second interval for data storage. The BIOSEN C-line Sport (EKF Diagnostic, Magdeburg, Germany) was used to measure blood lactate concentration from blood samples (20 μL) from the fingertip. The subjects' rating of perceived exertion (RPE) was registered using the Borg (6–20) scale [21].

The skiers were 2-D video recorded during submaximal treadmill roller skiing by using an Apple iPad 4 (MD791KN/A USA) with 30 frames per second, and the video recordings were analysed for cycle length and cycle rate in the software Coach Eye (TechSmit Corp USA). The iPad was placed at 90˚ to the skiing direction on the skiers' left side, 4.25 m from the centre of the skiing treadmill. Calculation of the average cycle characteristics was determined by timing 10 cycles and dividing them by 10, during the last 30 sec of the highest intensity in each condition (pole length, speed and inclination). Cycle time was taken from the time between two pole plants on the left side. Cycle length was calculated by multiplying the speed of the treadmill and the cycle time. Cycle rate was taken as the reciprocal of cycle time. Knee angle was taken at the lowest position, where the legs were parallel just before the left leg push. The two angle lines started at the position of the patella and touched the thigh and the leg (Fig 1).

The angles measured in the manner described above are not proper joint angles for the knee but were approximations which were judged to be more reproducible because

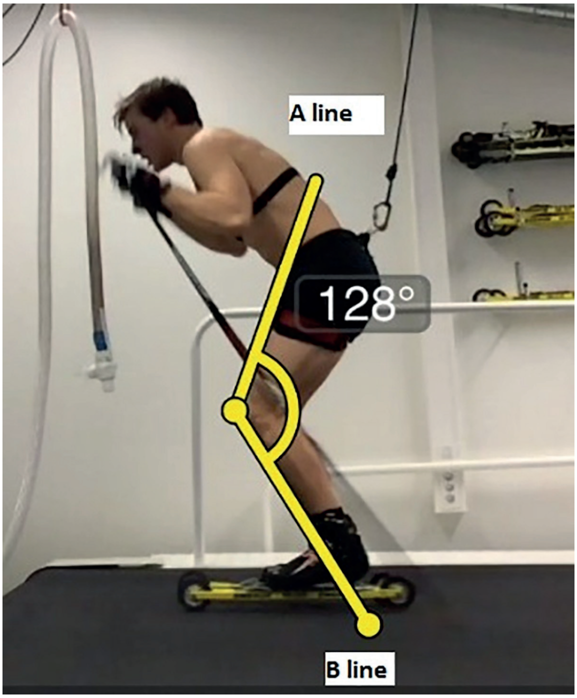


Fig 1. Illustration of knee angle measurements. Knee angle was determined at the lowest position where the legs were parallel just before left leg push. Lines A and B were drawn based on the front part of the thigh and shank. The skier shown in the figure signed a written consent form for usage of his image in this paper.

https://doi.org/10.1371/journal.pone.0211550.g001

estimations of hip, knee and ankle joint centres were not required. However, the reported angles were measured consistently for all skiers.

Statistical analyses

The data were confirmed to be normally distributed with the Shapiro-Wilk test, and all results are presented as means ± standard deviation (SD), except for the perceptual responses; these are presented as median and interquartile range (IQR). To compare the effect of pole length on physiological and perceptual responses during submaximal treadmill roller skiing, two (LP versus SSP) x three (either inclines [7, 9, 11%] or velocities [14, 17, 20 km/h]) repeated measures ANOVA were performed. Post-hoc comparisons with Bonferroni correction were conducted to detect differences. A one-way repeated measures ANOVA was applied to compare the effect of pole length on cycle characteristics and knee angles at the highest inclination (11%) and at the highest speed (20 $km \cdot h^{-1}$) in two separate analyses. Paired sample *t*-tests were applied when there were only two means to be compared (for example knee angle at 11% and 10 $km \cdot h^{-1}$ with a comparison of SSP vs. LP). The effect size was reported as Cohen´s *d* ($0 < d < 0.2$ considered to be a very small, $0.2 < d < 0.5$ a small, $0.5 < d < 0.8$ a medium and $d > 0.8$ a large effect) [22]. The level of statistical significance was set at $P \leq 0.05$. All statistical analyses were performed with the IBM SPSS Statistics for Windows, version 21.0 (IBM Corp., Armonk, NY, USA).

Results

Peak aerobic capacity and performance

The VO_{2peak} tested during uphill treadmill roller skiing at 4% inclination and a starting speed of 16 $km \cdot h^{-1}$ averaged 68.7 ± 3.8 $ml \cdot min^{-1} \cdot kg^{-1}$ and lasted for 418 ± 65 s. The average peak skiing speed was 26.6 ± 1.9 $km \cdot h^{-1}$, and the corresponding values for RER, HR_{peak} and blood lactate concentration were 1.12 ± 0.07, 197.3 ± 5.3 $beats \cdot min^{-1}$, and 10.03 ± 2.28 $mmol \cdot L^{-1}$, respectively. The median (IQR) RPE score was 19 (1.3).

Submaximal responses

Physiological, perceptual and kinematic variables for the two submaximal protocols are shown in Table 1 and Table 2. The VO_2-uptake relative to treadmill roller skiing VO_{2peak} for the submaximal protocol with fixed speed at 10 $km \cdot h^{-1}$ was 64 ± 4%, 74 ± 4% and 83 ± 4% at 7%, 9% and 11% inclination, respectively. The corresponding VO_2-values for the submaximal protocol with fixed inclination at 4% were 64 ± 4%, 73 ± 4% and 85 ± 5% of VO_{2max} at 14 $km \cdot h^{-1}$, 17 $km \cdot h^{-1}$ and 20 $km \cdot h^{-1}$, respectively. In both protocols, all physiological and perceptual variables increased with increasing intensity (i.e. increased inclination at fixed speed or increased speed at fixed inclination, all $P < 0.001$).

For the protocol with fixed speed at the steepest inclination (11%), the VO_2 was lower at 56.6 vs. 58.2 $ml \cdot min^{-1} \cdot kg^{-1}$ ($P = 0.005$, Cohen´s $d = 0.70$) and the GE was higher (18.8% vs. 18.2%, $P = 0.012$, Cohen´s $d = 0.71$) with LP than with SSP. At the same inclination, the knee

Table 1. Physiological and perceptual responses during uphill G3 roller skiing at three 5-minute submaximal workloads with increasing inclination at a fixed speed (10 $km \cdot h^{-1}$). Kinematic responses were obtained only during the steepest inclination (N = 10, mean ± SD).

	7%		9%		11%		ANOVA		
Parameter	SSP	LP	SSP	LP	SSP	LP	Pole length (PL)	Inclination (INC)	PL x INC
VO_2 ($ml \cdot min^{-1} \cdot kg^{-1}$)	44.5 ± 1.5	44.0 ± 2.0	52.0 ± 2.1	51.0 ± 2.1	58.2 ± 2.0	56.6 ± 2.6*	$F_{1.9}$ = 13.27##	$F_{2.18}$ = 241.20###	$F_{2.18}$ = 1.50
BLa ($mmol \cdot L^{-1}$)	1.76 ± 0.5	1.68 ± 0.5	2.58 ± 0.8	2.52 ± 0.8	4.35 ± 1.1	4.32 ± 1.2	$F_{1.9}$ = 0.80	$F_{2.18}$ = 92.05###	$F_{2.18}$ = 0.044
RER	0.87 ± 0.3	0.88 ± 0.3	0.91 ± 0.4	0.91 ± 0.3	0.94 ± 0.3	0.94 ± 0.4	$F_{1.9}$ = 0.94	$F_{2.18}$ = 69.10###	$F_{2.18}$ = 0.64
HR ($beats \cdot min^{-1}$)	156.7 ± 10.9	156.6 ± 11.1	173.4 ± 7.7	173.0 ± 8.2	184.6 ± 7.5	184.5 ± 7.0	$F_{1.9}$ = 0.19	$F_{2.18}$ = 158.74###	$F_{2.18}$ = 0.27
[a]RPE (6–20)	9.5 (3.3)	10.5 (4.0)	13.0 (1.3)	13.0 (1.3)	16.0 (1.5)	16.0 (2.0)	$F_{1.9}$ = 0.10	$F_{2.18}$ = 99.62###	$F_{2.18}$ = 1.04
Work rate (W)	186 ± 12		225 ± 14		265 ± 17				
Metabolic rate (W)	1103 ± 82	1079 ± 80	1292 ± 83	1274 ± 83	1458 ± 91	1418 ± 112**	$F_{1.9}$ = 5.52#	$F_{2.18}$ = 123.65###	$F_{2.18}$ = 0.47
Gross efficiency (%)	17.0 ± 0.6	17.2 ± 0.8	17.5 ± 0.8	17.9 ± 0.8	18.2 ± 0.7	18.8 ± 1.0*	$F_{1.9}$ = 14.08##	$F_{2.18}$ = 20.91###	$F_{2.18}$ = 0.60
Cycle length (m)					2.88 ± 0.1	2.89 ± 0.1			
Cycle rate (Hz)					0.96 ± 0.05	0.96 ± 0.05			
Knee angle (°)					126 ± 8	132 ± 7*			

SSP = self-selected pole length; LP = longer pole length (SSP + 7.5 cm); VO_2 = oxygen uptake; BLa = blood lactate concentration; RER = respiratory exchange ratio; HR = heart rate; RPE = ratings of perceived exertion.

[a] Presented as median and inter quartile range (IQR).

* Significant difference between the two pole lengths at the same inclination: *$P < 0.05$

**$P < 0.01$.

Main effect of pole length and main effect of inclination: #$P < 0.05$

$P < 0.01$

$P < 0.001$.

https://doi.org/10.1371/journal.pone.0211550.t001

Table 2. Physiological and perceptual responses during uphill G3 roller skiing at three 5-minute submaximal workloads with increasing speed at a fixed inclination (4%). Kinematic responses were obtained only during the highest speed (N = 10, mean ± SD).

	14 km·h^{-1}		**17 km·h^{-1}**		**20 km·h^{-1}**		**ANOVA**		
Parameter	**SSP**	**LP**	**SSP**	**LP**	**SSP**	**LP**	**Pole length (PL)**	**Speed (SP)**	**PL x SP**
$^1VO_2$ (ml·min^{-1}·kg^{-1})	44.8 ± 2.4	43.5 ± 3.1*	50.3 ± 1.6	50.1 ± 1.9	59.1 ± 2.5	57.9 ± 2.0**	$F_{1.8}$ = 12.59##	$F_{2.16}$ = 365.06###	$F_{2.16}$ = 1.32
BLa (mmol·L^{-1})	1.72 ± 0.56	1.71 ± 0.58	2.31 ± 0.68	2.31 ± 0.60	4.16 ± 1.25	3.87 ± 0.94	$F_{1.9}$ = 1.18	$F_{2.18}$ = 103.07###	$F_{2.18}$ = 2.91
RER	0.89 ± 0.03	0.89 ± 0.04	0.91 ± 0.03	0.91 ± 0.04	0.95 ± 0.04	0.94 ± 0.03	$F_{1.9}$ = 2.03	$F_{2.18}$ = 41.64###	$F_{2.18}$ = 0.06
HR (beats · min^{-1})	151.7 ± 13.0	152.9 ±13.0	169.5 ± 11.4	169.6 ± 8.6	183.2 ± 7.7	181.9 ± 7.7	$F_{1.9}$ = 0.000	$F_{2.18}$ = 151.96###	$F_{2.18}$ = 1.72
^{a}RPE (6–20)	10.5 (3.5)	10.0 (2.3)	13.0 (2.0)	13.0 (2.0)	16.0 (1.5)	16.0 (1.0)	$F_{1.9}$ = 0.14	$F_{2.18}$ = 108.0###	$F_{2.18}$ = 0.57
Work rate (W)	177 ± 11		215 ± 14		253 ± 16				
Metabolic rate (W)	1109 ±87	1070 ± 91	1276 ± 127	1244 ± 75	1504 ± 162	1454 ± 94	$F_{1.9}$ = 3.63	$F_{2.18}$ = 169.28###	$F_{2.18}$ = 0.37
^{1}Gross efficiency (%)	16.0 ± 0.9	16.6 ± 1.2*	16.9 ± 1.1	17.5 ± 0.7	16.9 ± 1.3	17.6 ± 0.8*	$F_{1.8}$ = 5.95#	$F_{2.16}$ = 6.77##	$F_{2.16}$ = 0.15
Cycle length (m)					5.67 ± 0.32	5.68 ± 0.42			
Cycle rate (Hz)					0.98 ± 0.06	0.98 ± 0.08			
Knee angle (°)					129 ± 3	135 ± 6**			

SSP = self-selected pole length; LP = longer pole length (SSP + 7.5 cm); VO_2 = oxygen uptake; BLa = blood lactate concentration; RER = respiratory exchange ratio; HR = heart rate; RPE = ratings of perceived exertion.

[1] N = 9.

[a] Presented as median and inter quartile range (IQR).

* Significant difference between the two pole lengths at the same inclination: *$P < 0.05$

**$P < 0.01$.

Main effect of pole length and main effect of speed: #$P < 0.05$

$P < 0.01$

$P < 0.001$.

https://doi.org/10.1371/journal.pone.0211550.t002

angle was 4.8% greater with LP than with SSP (P = 0.050, Cohen´s *d* = 0.80). At 9% inclination, there was a tendency towards lower VO_2-uptake (P = 0.056, Cohen´s *d* = 0.48) and higher GE (P = 0.059, Cohen´s *d* = 0.50) with LP.

For the protocol with fixed inclination, the VO_2-uptake was lower (43.5 vs. 44.8 ml·min^{-1}·kg^{-1}, P = 0.050, Cohen´s *d* = 0.47) and GE was higher (16.6% vs. 16.0%, P = 0.03, Cohen´s *d* = 0.57) with LP than with SSP at the lowest speed of 14 km·h^{-1}. At the highest speed of 20 km·h^{-1}, the VO_2-uptake was lower (57.9 vs. 59.1 ml·min^{-1}·kg^{-1}, P = 0.01, Cohen´s *d* = 0.53), GE was higher (17.6% vs. 16.9%, P = 0.03, Cohen´s *d* = 0.64) and the knee angle was 5.5% greater (P = 0.003, Cohen´s *d* = 1.3) with LP, when compared to SSP.

Discussion

The primary aim of this study was to investigate the effect of pole length on physiological and perceptual responses as a result of increasing speed and inclination for submaximal roller- skiing with the G3 ski skating sub-technique. The main findings in the current study were as follows: 1) LP induced lower VO_2-uptake and higher GE in the two highest submaximal workloads, i.e. at 11% inclination and at 20 km·h^{-1}, compared to SSP. 2) At 4% inclination and at the lowest speed of 14 km·h^{-1}, the VO_2-uptake was also lower and GE higher with LP compared to SSP. 3) The participants' RPE on SSP and LP at all conditions were not significantly different. 4) The LP showed a greater knee angle at the two highest submaximal workloads compared to SSP conditions. 5) Additionally, there were no significant differences in cycle characteristics between SSP and LP at the two highest submaximal workloads.

Effect of pole length on physiological and perceptual responses

Our findings in this particular study are in line with earlier investigations that claimed that longer poles in classic DP of up to ~ 90% of body height reduced the VO_2-cost [11, 12, 14]. In the present study, the skiers were tested in the G3 ski skating sub-technique, and since it is assumed that performance in DP and G3 are limited by the same physiological and biomechanical factors with respect to at least upper-body work [9, 10], it is reasonable to assume that LP in G3 have the same advantages. At the two highest submaximal workloads (4% inclination and 20 $km \cdot h^{-1}$, 11% inclination and 10 $km \cdot h^{-1}$) the skiers in our study had a lower VO_2-uptake and a higher GE when they used LP. The reason for this may be the biomechanical and muscular advantages of a more extended knee angle found in the lowest position. We only had rough estimations of knee angle in our study; however, with a greater knee angle in the skier´s lowest position, the skiers may end up in a more upright posture with less vertical displacement of COM. In addition, the effect of lower VO_2-cost and higher GE due to LP than SSP was more pronounced in the steep uphill protocol than in the high speed protocol. Considered together with the interesting findings on DP of Losnegard [11] and Carlsen [12], it seems that the benefit of longer poles increases with steeper uphill terrain. This may be due to greater propulsive force, as longer poles allow the skier to use the upper body and body mass more effectively [15, 23]. Since most of the racing time is spent on uphill sections during a race and the greatest time differences between skiers occur on uphills [4], the novel findings in our study indicate that LP in G3 may enhance uphill performance and significantly influence race outcomes. However, in a more upright position using longer poles, the area of the skier might be larger and therefore also the air drag. Due to the low speed in uphill terrain, this would have a marginal or non-existing effect on our results but should be considered in flatter terrain where higher speeds are employed.

The knee-extension flexion pattern, performed from a higher position when LP were used, may be related to the lower VO_2-cost. The SSP conditions showed that the skier was brought into positions where the external moment arm in the knee joint becomes greater than in LP conditions. The less extended knee joint at the lowest position before the kick starts with SSP will lead to more muscular loading, which could also lead to higher VO_2-cost. Since the VO_2-cost was lower and no differences in cycle characteristics were measured in this study, LP produces speed effectively even with the knee joint more extended than in the SSP condition, which may also be due to a more effective use of the upper body. The reason for the lower VO_2-cost with longer poles in the research of DP cannot solely be explained by the reduced vertical displacement of COM. The reason for this is that the differences of COM between long and short poles are relatively small (1cm) [11, 12]. On the other hand, it is important not to underestimate small differences, in for example knee angle, in endurance sports like XC skiing, since every movement is repeated many times. Interestingly, skiers, even at the highest international level, have not utilised the potential of longer poles, approved by the FIS rules (FIS §343.8.2). However, the translation of our results to on-snow G3 skiing should be further investigated, and future studies are warranted to better understand which mechanisms may play a part in explaining the reduced physiological cost of uphill ski skating with longer poles.

The 4% and 14 $km \cdot h^{-1}$ conditions also showed a lower VO_2-cost and greater GE for LP. This metabolic rate corresponds to intensity zone 1 (I1) and is the most used training intensity zone for XC skiers. The 4% and 17 $km \cdot h^{-1}$ conditions correspond to a metabolic rate at intensity zone two (I2) which is the training intensity zone XC skiers try to reduce to avoid fatigue in daily training [24]. The volume of specific training at the lowest (I1) and highest submaximal (I3) workloads (inclination and speed) may be the reason for a more effective use of LP in these two conditions (I1 and I3). However, there was no significant difference between SSP and LP at 4% and 17 $km \cdot h^{-1}$.

During G3 skiing, the differences in cycle characteristics between SSP and LP were only measured at the two highest submaximal workloads (10 km·h^{-1} and 11% inclination, and 4% inclination and 20 km·h^{-1}). No significant effect of pole length on cycle characteristics was found. In earlier studies [11, 12, 14], it was shown that pole length affected both kinematics and kinetics in DP. In these studies, increased pole length resulted in longer ground contact times, increased cycle length and reduced poling rate, which led to a more energetic and efficient poling technique. One reason for not finding differences in cycle characteristics between different pole lengths in the G3 technique in the current study may be that the leg push-off compensates in skate skiing, which is not possible when merely DP. Another explanation may be that we did not measure at maximal workloads, in contrast to the DP research.

The participants reported no significant differences in RPE with the use of LP and SSP in any of the three submaximal workloads. This corresponds well with our findings of no differences in RER and BLa between conditions. However, these findings contrast with anecdotes from the XC skiing community about the disadvantage of longer poles in a slower pole recovery phase and the aim to ski with 'low shoulders' in the repositioning phase, in addition to the fact that longer poles have increased mass and increased moment of inertia.

After testing, the skiers in this study did not give any negative feedback related to the use of LP compared to SSP. The performance in XC skiing will always be compromised by choice of sub-technique and equipment due to changing snow, weather and track conditions during a race. Hence, in optimal conditions and with practice, longer poles may be a suitable strategy in the G3 technique to enhance performance.

Strengths, limitations and practical applications

Standard test methodology of physiology and RPE was utilised to evaluate the effects of pole length in the G3 technique in uphill skate skiing. Data in this study indicate that skiers might consider experimenting with longer poles in skate skiing to increase their performance. However, a direct translation to on-snow skiing and competitions (e.g. time trials) needs to be established in future research. In the lab, the measurement of kinematics, COM, range of motion and angles of the important joints in the skiing sub-techniques in particular should be analysed further with appropriate equipment and methods. Such information will enhance understanding of how VO_2-cost is influenced by pole length. Furthermore, the ~2 ml · min^{-1} · kg^{-1} lower VO_2-cost with LP on the uphill section has to be seen from the perspective that the reduced VO_2-cost can be used to increase performance in cross-country skiing. However, some uphills in the world cup tracks are so steep that they probably are still best climbed, even for the strongest skiers, by using the G2 technique. However, considering that these steep uphills form a small part of the track, long poles could still provide a total better performance despite being a disadvantage on such terrain. The possible disadvantage of using longer poles on these steep uphill sections is unlikely to be so extreme as to exclude a possible effective use of the G2 technique. There is also a possibility that long poles may not be as stiff as shorter ones, which may lead to lower force transfer to the ground and forward propulsion. However, we do not know if long poles have any disadvantages in the G2 technique or in the issues mentioned above; this must therefore be further investigated under snow conditions. Long poles can also be a disadvantage in mass starts, sprints and relays because of the increased risk of broken poles due to a slightly wider pole plant. A shortcoming in this study is that we were unable to determine whether even longer poles would be still more beneficial or if the effect would be reduced. Further, we suggest a future long-term training study to investigate the effect of long poles. To evaluate training adaptations and the effect of long poles, an on-snow time trial performance test should be performed. The vast majority of research on this topic has been conducted in classic skiing; the present study therefore had to rely on this knowledge and use a similar methodological approach, since this is the first scientific work on this topic in skate skiing.

Conclusions

The novel finding of this study is the superiority of longer poles over self-selected poles in G3 uphill ski skating sub-technique in terms of gross efficiency and VO_2-cost both on uphill and at high speed on flatter terrain. Moreover, these results were associated with a more extended knee angle in the lowest position when using longer rather than self-selected poles. This latter finding may indicate that skiers have less vertical displacement when using longer poles, which can, at least partly, explain the lower VO_2-cost and higher gross efficiency. While skier ratings of perceived exertion were not different between pole lengths at any of the submaximal workloads, clear differences of economy were observed. It is likely that cross-country skiers who choose longer poles rather than the typically preferred pole length have a modest metabolic advantage in G3 skating. Future studies should examine to what extent pole ground contact time and pole force effectiveness could explain the benefits of pole length in skating, and whether our findings would apply during outdoor on-snow skiing where air drag also plays a role.

Supporting information

S1 File. Supporting data.
(XLSX)

Author Contributions

Conceptualization: Per-Øyvind Torvik, Erna Dianne von Heimburg, Torkel Sende, Boye Welde.

Data curation: Per-Øyvind Torvik, Torkel Sende, Boye Welde.

Formal analysis: Per-Øyvind Torvik, Erna Dianne von Heimburg, Boye Welde.

Investigation: Per-Øyvind Torvik, Erna Dianne von Heimburg, Torkel Sende, Boye Welde.

Methodology: Per-Øyvind Torvik, Erna Dianne von Heimburg, Torkel Sende, Boye Welde.

Project administration: Per-Øyvind Torvik.

Validation: Per-Øyvind Torvik, Boye Welde.

Visualization: Per-Øyvind Torvik, Boye Welde.

Writing – original draft: Per-Øyvind Torvik.

Writing – review & editing: Torkel Sende.

References

1. Sandbakk Ø, Holmberg HC. Physiological capacity and training routines of elite cross-country skiers: Approaching the upper limits of human endurance. Int J Sport Physiol Perform 2017; 12: 1003–1011.
2. Andersson E, Supej M, Sandbakk Ø, 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. https://doi.org/10.1007/s00421-010-1535-2 PMID: 20571822
3. Bolger C, Kocbach J, Hegge AM, Sandbakk Ø. Speed and heart-rate profiles in skating and classical cross-country-skiing competitions. Int J Sport Physiol Perform 2015: 10: 873–880.

4. Sandbakk Ø, Hegge AM, Losnegard T, Skattebo Ø, Tønnessen E, Holmberg HC. The physiological capacity of the world's highest ranked female cross-country skiers. Med Sci Sports Exerc. 2016; 48(6): 1091–100. https://doi.org/10.1249/MSS.0000000000000862 PMID: 26741124.
5. 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. https://doi.org/10.3389/fphys.2016.00326 PMID: 27536245; Central PMCID: PMCPMC4971020.
6. Kvamme B, Jakobsen V, Hetland S, Smith G. Ski skating technique and physiological responses across slopes and speeds. Eur J Appl Physiol. 2005; 95: 205–212. https://doi.org/10.1007/s00421-005-1332-5 PMID: 16003540
7. Nilsson J, Jakobsen V, Tveit P, Eikrehagen O. Pole length and ground reaction forces during maximal double poling in skiing. Sports Biomech. 2003; 2(2): 227–236. https://doi.org/10.1080/14763140308522820 PMID: 14737930.
8. Bengtsson BE. Cross-country skating: How it started. International Skiing History Association. Available from: https://skiinghistory.org/history/cross-country-skating-how-it-started Cited 27 September 2018.
9. Myklebust H, Losnegard T. Hallén J. Differences in V1 and V2 ski skating techniques described by accelerometer. Scand J Med Sci Sports. 2014; 24: 882–893. https://doi.org/10.1111/sms.12106 PMID: 23957331
10. Sandbakk Ø, Leirdal S, Ettema G. The physiological and biomechanical differences between double poling and G3 skating in world class cross-country skiers. Eur J Appl Physiol. 2015; 115(3): 483–487. https://doi.org/10.1007/s00421-014-3039-y PMID: 25362527
11. Losnegard T, Myklebust H, Skattebo Ø, Stadheim HK, Sandbakk Ø, Hallen J. The influence of pole length on performance, O2 cost, and kinematics in double poling. Int J Sport Physiol Perform. 2017b; 12: 211–217. https://doi.org/10.1123/ijspp.2015-0754 PMID: 27193356.
12. Carlsen C, Rud B, Myklebust H, Losnegard T. Pole lengths influence O_2 cost during double poling in higly trained cross country skiers. Eur J Appl Physiol. 2018;271–281. https://doi.org/10.1007/s00421-017-3767-x PMID: 29196845
13. Hansen EA, Losnegard T. Pole length affects cross-country skiers' performance in an 80-m double poling trial performed on snow from standing start. Sports Eng. 2010; 12(4): 171–178.
14. Onasch F, Killick A, Herzog W. Is there an optimal pole length for double poling in cross country skiing? J Appl Biomec. 2017; 33: 197–202.
15. Holmberg HC, Lindinger S, Stöggl T, Eitzlmair E, Müller E. Biomechanical analysis of double poling in elite cross-country skiers. Med Sci Sports Exerc. 2005; 37: 807–818. PMID: 15870635.
16. Frøyd C, Madsen Ø, Tønnessen E, Wisnes AR, Aasen S. Utholdenhet—trening som gir resultater [Endurance: Training that gives results]. Akilles 1st. Oslo 2005.
17. Vandbakk K, Welde B, Kruken AH, Baumgart J, Ettema G, Karlsen T, et al. Effects of upper-body sprint-interval training on strength and endurance capacities in female cross-country skiers. PLOS ONE. 2017; 12(2): 1–17.
18. Midgley AW, McNaughton LR, Polman R, Marchant D. Criteria for determination of maximal oxygen uptake: A brief critique and recommendations for future research. Sports Med. 2007; 37: 1019–1028. https://doi.org/10.2165/00007256-200737120-00002 PMID: 18027991
19. 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. https://doi.org/10.1007/s00421-010-1372-3 PMID: 20151149
20. Péronnet F, Massicotte D. Table of nonprotein respiratory quotient: An update. Can J Sport Sci. 1991; 16(1): 23–29. PMID: 1645211
21. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 1982; 14: 377–381. PMID: 7154893.
22. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale: Erlbaum Associates; 1988.
23. Stöggl TL, Holmberg HC. Double-poling biomechanics of elite cross-country skiers: Flat versus uphill terrain. Med Sci Sports Exerc. 2016; 48: 1580–1589. https://doi.org/10.1249/MSS.0000000000000943 PMID: 27031747.
24. Stöggl T, Sperlich B. Polarized training has greater impact on the key endurance variables than threshold, high intensity, or high volume training. Front Physiol. 2014; 5(33): 1–9.

Study V

Journal of Science in Sport and Exercise (2021) 3:348–354
https://doi.org/10.1007/s42978-021-00134-0

ORIGINAL ARTICLE

Pole Length Influences Performance During On-Snow Skating in Female Cross-Country Skiers

Per-Øyvind Torvik[1] · **Roland van den Tillaar**[1] · **Guro Bostad**[1] · **Øyvind Sandbakk**[2]

Received: 17 March 2020 / Accepted: 24 July 2021 / Published online: 27 October 2021

Abstract

Purpose The purpose of this study was to examine the effect of pole length on performance and technique selection during a simulated skating cross-country (XC) skiing competition on snow in female XC skiers.

Methods Nine female XC skiers and biathletes (VO_{2max} 63.6 ± 6.2 mL/min/kg, age 22.9 ± 3.5 years, body height 1.69 ± 0.1 m and body mass 60.8 ± 4.6 kg) completed two 5-km skating time-trail with maximal effort. The athletes had a minimum 4.5 h of rest between the two races, which were performed in a random order: one with self-selected poles (89.0% ± 0.6% of body height) and one with 7.5 cm increased pole length (94.0% ± 0.5% of body height). Speed in set terrain sections was determined and the selection of sub-technique was self-reported immediately after each race based on a detailed review of the entire track.

Results Skiers performed on average 7.1 ± 7.1 s ($P = 0.029$) faster with the long poles, with this difference occurring during the first 200 m and in the uphill parts of the track, in which ~ 5% more G3 and ~ 5% fewer G2 sub-techniques were chosen (both $P < 0.05$). The rating of perceived exertion was 1 ± 0.9 point lower ($P = 0.04$) and skiing technique was perceived to be ~ 1.2 ± 1.5 points better with long poles ($P = 0.038$), while the physiological responses (i.e., peak and average heart rate, and blood lactate concentration) did not differ between trials.

Conclusion In conclusion, poles 7.5 cm longer than self-selected ones improved performance in skating, by enhancing speed in the initial phase (first 200 m) and in the uphill section of the track. In addition, the longer poles induced more use of the G3 skating sub-technique.

Keywords XC skiing · Skiing performance · Skiing equipment · Sub-technique selection

Introduction

In cross-country (XC) skiing, skiers propel themselves forward by combining ski push-offs and poling. Accordingly, the characteristics of the skis and poles are crucial for the effectiveness of most skiing technique in both classical and skating styles. Previously, the use of longer poles has been shown to increase skiing efficiency and performance in double poling [5, 13, 14, 17] and in the G3 skating technique on roller skis [29]. Moreover, two previous studies showed positive effects of increased pole length on snow in the classical style [8, 30]. Although there are indications from the above-mentioned study on G3 roller ski skating [29] that increased pole length could be beneficial in skating, at least in some of the sub-techniques, this has not yet been examined while ski skating on snow.

The use of longer poles in the classical style together with better equipment and preparation of the track [21] as well as a stronger and more endurance trained upper body [18] have contributed to make double poling one of the most favored classical sub-techniques used in races. Today double poling is widely employed even in uphill sections by both male and female cross-country skiers [5, 9, 17, 24]. In classical races, the benefits of longer poles led to restrictions in pole length and the inclusion of diagonal zones in competitions [6]. However, the possible benefits of longer poles in the skating technique have not been systematically evaluated and the poles in skating are only limited to the skier's body height [6].

✉ Per-Øyvind Torvik
per-o-torvik@nord.no

[1] Department of Sports Sciences and Physical Education, Nord University, Levanger, Norway

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

A potential effect on performance of increased pole length may be associated with changes in the fractional use of the five different skating sub-techniques (G1-5). The G2, G3 and G4 techniques are the most favored sub-techniques in skating [12, 16]. Among these, the two most investigated sub-techniques are G2 [2, 4, 11, 22, 26], which is mainly used on steep uphill stretches and when accelerating, and G3, a technique normally used on flat and slightly uphill terrain. Interestingly, Myklebust et al. [15] reported that the G3 technique was limited by the same factors as double poling, especially concerning the way potential energy is gained between pole plants, the propulsive force in the poling action, and the conformity in upper-body muscle work. This highlights a particular potential to enhance G3 speed and thereby use this sub-technique over a wider range of terrain using longer poles. The mechanisms behind enhanced performance and reduced O_2 cost of longer poles in double poling has recently been examined by several researchers [5, 13, 17], showing that double poling with longer poles in low to moderate uphill terrain resulted in reduced vertical displacement of the center of mass (CoM), and longer poling time. To what extent these findings also apply to the skating technique has not yet been examined.

The question of finding the optimal pole length in skating has been a “hot topic” since skiers in 1985 started to use the skating technique systematically during World Cup events [1], and until now 7.5–10 cm longer poles (~90% of body height) than those used in classical style have been regarded as beneficial. However, this has been sparsely evaluated scientifically, and to our knowledge has not changed significantly since 1985. Longer poles have certainly not been systematically evaluated in female XC skiers despite the fact that longer pole lengths are now considered more effective in uphill roller ski skating on a treadmill [29] in double poling [5, 17] but not in the other classical sub-techniques [30], which may indicate that a positive effect could also apply to skating. Trøen et al. [30], however, included seven females in his studies of classic ski technique on snow and reported an even greater effect for females than males in double poling with longer poles. However, the potential benefit of using longer poles in skating should be further explored on snow, including how pole length affects the skier’s choice of different sub-techniques across hilly terrain.

Therefore, this study investigated the effect of increased pole length on performance and selection of sub-technique during on-snow ski skating in female skiers. It was hypothesized that longer poles would lead to improved performance through greater use of the G3 skating technique.

Materials and Methods

Participants

Nine competitive female junior and senior skiers (maximal oxygen uptake in running: 63.6 ± 6.2 mL/min/kg, FIS points: 100.2 ± 33.2, maximal heart rate: 197 ± 7 beats/min, age: 22.9 ± 3.5 years, height: 1.69 ± 0.1 m and body mass: 60.8 ± 4.6 kg), participated in this study. The participants had competed at national and international level for 6.0 ± 2.0 years. They were not familiar with using longer poles than their regular ones at the time of the study. The participants provided written informed consent to participate in the study, which was recommended by the Norwegian Center for Research Data and performed according to the Declaration of Helsinki. All participants were 18 years or older at the start of the study.

Design

To compare the effects of self-selected and longer (self-selected + 7.5 cm) skating poles upon skiing performance, selection of sub-technique, as well as physiological and perceptual responses during a simulated competition, two 5-km time trial races on an internationally approved track were carried out on the same day using a randomized cross-over design, acting like their own controls. Five skiers started with the self-selected poles and four started with the +7.5 cm poles. All skiers had a minimum of 4.5 h rest between each time trial. On separate days, 5–7 days before the time trials, all skiers were tested for maximal oxygen uptake (VO_{2max}) in the laboratory and maximal heart rate (HR_{max}) in uphill running outdoors. VO_{2max} was tested to describe the aerobic endurance level of the athletes in a standard incremental uphill running test at 10.0% inclination on a motor-driven treadmill, with increasing speed every minute until exhaustion, with a protocol and procedures published previously [28]. Similarly, maximal heart rate was tested in an outdoor uphill running test, also with a protocol and procedures published previously [10].

Procedure

The participants prepared for all tests as they would for a regular competition [31], except that a standard warm-up was performed. In the 24 h preceding all tests, the participants were instructed to eat their typical diet when preparing for a competition, and had to avoid strenuous exercise, caffeine, and alcohol. Each participant arrived in the laboratory or at the ski venue one hour before each test for a short interview, to ensure that they were well nourished, hydrated, motivated and healthy. A standard warm-up, consisting of 15-min running at ~ 60%–70% of maximum HR was performed before all tests. The subjects had at least five hours between each time trial and were instructed to have total rest in the final two hours before warm-up for test 2.

The time trial tests were performed as simulated 5-km competitions in the skating technique, with participants with the lowest FIS points starting first, and a 1-min start interval, to avoid any interference between athletes. The participants started randomly with self-selected or longer poles. The self-selected pole length was 89.0% ± 1.0% of the participant's body height, while the longer pole length was 94.0% ± 1.0% of body height. Other ski equipment was individualized to the specific skiers' racing preferences, including racing suits, boot style, ski length and ski base material. All skiers were instructed to use their own skis for the prevailing conditions; these were only used for the two time trials, while other skis were used for warming up and cooling down. All skis were stone ground and prepared with a 1 mm hand structured linear roller (Swix, Norway) on the back of each ski. All skis were prepared with an LF 7 glide wax (Swix, Norway), and an LDF liquid glide topping (Vauhti, Finland) was used before each time trial. The track was prepared with a Pisten Bully 600 snowmobile, and the snow was hard-packed with similar conditions during the entire experiment. The weather conditions were measured at the start of each race with a digital weather station (Metnet, Norway), and weather and snow conditions were stable during the test day. The air temperature during the test day ranged between – 2.0° and – 0.9°, and the snow temperature from – 4.0° to – 4.7° (T95 Swix Snow Thermometer, Norway). The wind was 0–2 m/s from the north-east, the barometric pressure was from 1055 to 1079 mmHg and there was thin high cloud the whole day. Possible changes in the coefficient of snow ski friction were not measured between the two time trials, but the time spent in the longest straight downhill segment was used as an indirect measure of friction, which revealed no differences.

Heart rate was measured continuously and the average heart rate for the entire 5 km was determined. At the end of each time trial, blood lactate concentration and rate of perceived exertion (RPE) were assessed. Finally, the skiers were asked to evaluate their experience of skiing with the longer poles, when compared to the self-chosen poles, on a custom-made scale from 1 to 10, where 10 was defined as a much better feeling, 5 no difference and 1 as a much worse feeling. The evaluation applied to each of the five sections of the track.

Instruments and Measurements

In the outdoor time trial test, the blood lactate concentration of 5-μL samples was taken from the fingertip and analyzed using a Lactate Pro LT-1710*t* kit (Arkray Inc., Kyoto, Japan). The subjects' RPE was recorded using the Borg (6–20) scale [17]. Course and elevation profiles were determined with a Catapult Optimeye S5 (Cat-S5) (Catapult Sports, Melbourne, Australia) global navigation satellite system standalone receiver with an external antenna and mass of ~ 67 g. The Cat-S5 has recently been validated [7, 19] with a reported section time error of between 0.1 and 0.2 s for 20- to 180-m-long sections, and with errors in section time plateauing for longer sections [3, 19]. The tracks were 10–15 m wide, located in an area with minimal tree cover and no natural geographical features to interfere with GPS signals. To ensure correct GPS fixing and minimize inaccuracy, the Garmin GPS devices were turned on at least 20 min before the start of testing and blinded for the participants to prevent them using them for any guidance during the time trials.

The participants were timed with an Ipad Air1475 (Apple Inc., California, USA) using the RaceSplitter timing application version 1.7.6 (Makalu Interactive LLC, Delaware, USA). A questionnaire was constructed and used immediately after each of the time trial tests, which, combined with a subsequent interview with each participant directly after the races and visual observations by test leaders, was used to identify where the participants used the G2, G3, G4 skating sub-techniques on the track. Figure 1 is used to help the athletes to point out accurately where the transitions between techniques were made (Fig. 1). All skiers trained almost daily in this track, had previous experience with this procedure and were asked to notice exactly where they switched between different sub-techniques during the simulated competitions.

The track was 5.2 km (i.e. 2 laps of 2.5 km plus 200 m), which was divided into five 1-km track sections (S1–S5),

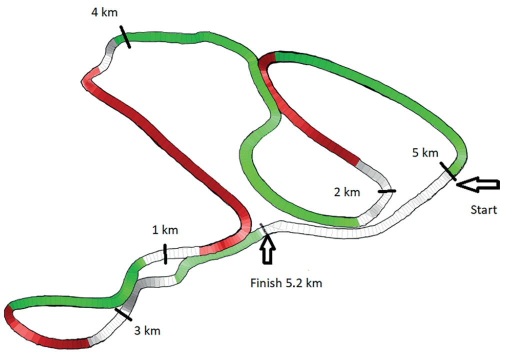


Fig. 1 Profile of the entire 5.2-km track (i.e. 2 laps of 2.5 km plus 200 m) used in the simulated competition. Uphill, flat and downhill terrains are marked with red, white/gray and green colors, respectively

]

according to distance from start (see Fig. 1). Section 1 consisted of varied terrain, while section 2 included two hills with mean inclines of 9.3% and 5.7% and lengths of 259 m (26-m climb) and 272 m (19-m climb), respectively. Section 3 contained varied terrain and included two short hills with 5 and 8 m climbs in the start of the section and the longest uphill of 396 m (41-m climb) with a mean incline of 9.3%. Section 4 included the longest downhill section of the track. The two main downhill parts of the track contained inclines of 7.8% and 5.8% for lengths of 407 m and 182 m in sections 2 and 4, respectively. Section 5 included an uphill of 272 m (19-m climb where the steepest part was 18.6%), followed by a 200-m flat segment. The maximal difference in elevation was 41.5 m with a total climb of 176 m for the entire track. The time each skier spent in each of the five sections was calculated based on split times. Speed for each section was calculated by dividing the length of a section by the time elapsed within that section.

Statistical Analysis

The Shapiro–Wilk test confirmed that data did not deviate from normal distribution, and all results are presented as means ± standard deviation (SD), except for the perceptual responses, which are presented as medians (IQR). To compare the differences in race time, use of sub-technique, as well as physiological and perceptual responses between the two time trials (long poles versus self-selected pole length), a one-way analysis of variance (ANOVA) with repeated measures was performed on each variable. To compare RPE between the two time trials, a Wilcoxon ranked sign test was applied. To identify the differences in time between the time trials for each km, a 2 (condition) × 5 (1–5 km) ANOVA was performed. Post hoc comparisons with the smallest mean differences were performed for pairwise comparisons between the different sections. The effect size reported in this study was eta squared (η^2), where $0.01 \leq \eta^2 < 0.06$ constituted a small effect, $0.06 \leq \eta^2 < 0.14$ a medium effect, and $\eta^2 > 0.14$ a large effect. The level of significance was set at $P < 0.05$ for all tests and the analyses were carried out with SPSS Statistics v26 (IBM Corp., Armonk, NY, USA).

Results

Time Trial Performance

There were no significant differences in the average time spent on the entire 5-km track between test one in the morning and test two in the afternoon (5.4 s faster), independent of pole length. The total time used for the 5 km was 7.1 ± 7.1 s shorter ($F = 7.1$, $P = 0.029$, $\eta^2 = 0.47$) when using the 7.5 cm longer poles (867.4 ± 58.4 s) than self-selected poles (874.3 ± 55.8 s). When divided into split times, the third km that included the longest uphill section of the track was significantly faster (by ~ 4 s) with the longer than with the self-selected poles ($P < 0.001$). In addition, the first 200 m were also faster (by ~ 2.7 s) with the long poles compared with the self-selected ones ($P < 0.05$; Fig. 2). The other sections and the final 200 m did not differ in performance between the two pole conditions.

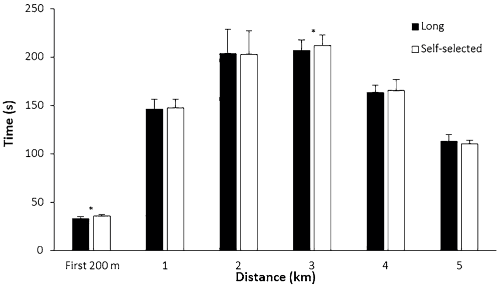


Fig. 2 The influence of pole length on performance in the five sections of the track, as well as the first 200 m. *Indicates a significant time difference between the two pole lengths

Table 1 Physiological and perceptual responses after 5-km cross-country skiing with self-selected and long (+7.5 cm) poles

	Self-selected	Long poles
Peak heart rate (beats/min)	184.7 ± 7.4	185.2 ± 7.7
Percentage of max heart rate (%)	88.2 ± 3.2	87.9 ± 3.2
Average heart rate (beats/min)	174.0 ± 7.1	173.4 ± 7.1
Percentage of max heart rate (%)	93.6 ± 3.2	93.8 ± 2.8
Lactate concentration (mmol/L)	9.4 ± 2.0	9.2 ± 2.3
RPE (6–20)	16.8 ± 1.0*	15.9 ± 0.9

*Indicates a significant difference between the two conditions, $P < 0.05$

No physiological responses differed between the two conditions ($F \leq 0.7$, $P \geq 0.46$, $\eta^2 \leq 0.07$). However, a significantly lower RPE ($P = 0.046$) was observed with the long poles compared with the self-selected poles (Table 1). The perception of skiing technique with long poles showed a mean value of 6.2 ± 1.5, which was 1.2 points above the score for self-selected poles ($P = 0.038$).

The distribution of different sub-techniques used during the 5 km was reported differently between the two conditions (Table 2; $F = 28.7$, $P < 0.001$, $\eta^2 = 0.78$). When the skiers were equipped with 7.5 cm longer poles, they reported using G3 five percentage points more than the G2 sub-technique; G3 was used further up on uphill sections before they switched to G2. The use of other sub-techniques did not significantly differ.

Discussion

The main findings in this study were that: (1) long poles enhanced performance compared to self-selected poles, without any alterations in average heart rate, blood lactate concentration and RPE, (2) the use of longer poles led to more use of the G3 sub-technique at the expense of G2 in the uphill sections of the track, and (3) the skiers reported lower RPE and a substantially better perception of the skiing technique when using long poles compared to their self-selected ones.

Our findings of better performance with long compared to self-selected poles in this study are in line with earlier investigations claiming that longer poles enhanced performance and reduced O_2 cost during both uphill treadmill roller skiing with the G3 skating technique [29] and uphill double poling while roller skiing on a treadmill [5, 13, 14, 17]. In the present study, the effect of pole length was tested on snow using the skating technique for the first time. We found significant performance improvements with 7.5 cm longer poles compared to self-selected ones, which were mainly related to enhanced performance in the first 200 m and during the longest uphill in section 3. While the superior improvement in the initial 200 m may be explained by faster acceleration, as previously shown for double poling in the studies by Hansen, Losnegard [8] and Losnegard et al. [14], better section 3 performance was probably due to enhanced performance in the longest uphill section, where skiers reported more use of the G3 technique with longer poles. Since it is assumed that performance in G3 and double poling has clear similarities in the contribution of the upper body to forward propulsion [15], it is reasonable to assume that the improved uphill performance with longer poles in skating on snow found here would be explained by the same mechanisms as previously found in double poling on a treadmill [5, 13, 17, 30]. Here, longer poles resulted in lower O_2 cost, which was associated with reduced vertical displacement of CoM and longer poling time.

Table 2 Reported distribution of different techniques (%) used during the 5-km cross-country race with self-selected and long (+7.5 cm) poles, exclusive of skating without poles, tucks and turns

	G3	G2	G4
Self-selected	66.4 ± 20.5	19.7 ± 10.3	14.4 ± 10.4
Long poles	71.6 ± 20.0*	14.9 ± 9.1*	13.7 ± 11.0

*Indicates a significant difference between the two conditions for this sub-technique, $P < 0.05$

In a previous publication [29], we reported a higher gross efficiency with long poles compared to self-selected ones in G3 skating at 11% uphill inclination and 10 km/h in roller skiing on a treadmill. This supports the present study, where the skiers reported more use of G3 in uphill sections of the track (9.3% incline and average speed of 13.5 km/h) with longer poles. The effectiveness of using longer poles in uphill skating may be explained by a higher start position for poling and thereby a more upright position with reduced vertical displacement of the CoM, as also found in skating by Torvik et al. [29]. A smaller distance between CoM and pole plant in double poling has also been pointed out by Carlsen et al. [5] and Losnegard et al. [14]. Notably, the enhanced performance found in the present study was found with equal physical strain, and with slightly lower perceived exertion with longer poles.

The possible benefit of long poles in uphill terrain is interesting, since most of the racing time is spent on uphill sections during a race and the greatest time differences between skiers occur there [19]. However, it is not known to what extent lower speed or steeper incline determine the positive effect of increased pole length. Indeed, speed and incline are interrelated, and cycle characteristics and the choice of sub-technique seem to be influenced by both factors when they are isolated. However, the fact that longer poles are most effective at lower speeds, which take place at steeper inclines and at the start when accelerating from zero, indicates that speed might be an important contributor. Because of the lower speeds among women, longer poles might be more beneficial for women than men. While Trøen et al. [30] indicated that this is the case in the classic style, this aspect needs to be further examined in skating.

We expected the last 200-m sprint towards the finishing line to be negatively affected by the long poles due to possible problems with rapid repositioning and maintenance of frequency. However, no such disadvantage was found although none of the skiers was used to skiing with longer poles. In fact, the lack of experience with longer poles indicates that extensive practice with long poles may enhance performance even more. This was exemplified by closer analysis of the data, showing that the only skier who did not benefit from longer poles over the entire 5-km time trial lost 10 s during the first 2 km. Our communication with the athlete revealed that she struggled to find the right technique for "timing" the pole plants in the first 2 km. However, this participant was also 5 s faster with the long poles in section 3, which had the longest uphill section of the track. In addition, the two athletes with the lowest FIS points and best performance during the time trial had the greatest effect from the long poles, with 14 and 16 s improvement. This is not unexpected since these two skiers probably have the best potential for utilizing longer poles, with a well-developed technique and upper-body capacity [25]. However, due to the small number of athletes participating in this study, results should be interpreted with caution and further studies with a high number of athletes and a wider range of performance levels would be required to draw firm conclusions.

Despite the lack of practice with longer poles, the participants reported a significantly better perception of skiing technique (i.e., a better feeling) when skiing with longer than with self-selected poles. However, it should be noted that four of the skiers reported that one short 25-m steep uphill section 500 m from the finishing line was challenging with long poles, due to longer repositioning of the long poles in the G2 sub-technique. Overall, we suggest that with extended practice, longer poles may be a strategy to enhance performance in ski skating. Although Losnegard et al. [14] did not find such an effect of practice with long poles in double poling, it is worth noting that the present study examined skating, where the movement pattern is more complex than in double poling.

Limitations

Detailed questionnaires and communication with the athletes were used to estimate the use of skating sub-technique in this study. Although there are clear limitations to this method and future approaches should include automatic detection of sub-techniques as implemented previously in the classical style by, e.g., Seeberg et al. [20] and Solli et al. [23], no previous studies had provided valid algorithms for skating [15, 27]. Although there are clear limitations to this methodology, all the athletes involved in this study had trained for several hundred hours and regularly performed competitions in this track over several years. Accordingly, we believe that they had a sound basis for judging their use of sub-technique, although we do not have reliable data or evidence to state the precise accuracy.

Although there were only nine participants in this study, the data indicated that skiers should consider experimenting with longer poles in ski skating, while a direct translation to competitions may require extensive practice and experience with different types of tracks, snow and weather conditions. In addition, a further understanding of the underlying mechanisms is required, in which information on temporal patterns and joint kinematics in the different skiing sub-techniques with various pole lengths on snow outdoors should be analyzed further.

Conclusions

This study demonstrates that increasing pole length by 7.5 cm in on-snow ski skating can be beneficial. Here, the performance improvement induced by longer poles occurred in the initial part of the race and the longest uphill section, which coincided with more use of the G3 sub-technique than G2. Since this took place without any changes in physiological parameters, but with improved perceived feeling and lower RPE with the long poles, we conclude that female XC skiers may enhance performance by choosing longer poles than those preferred in skating today.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42978-021-00134-0.

Funding We had no specific funding for this work.

Data Availability All relevant data are within the paper and its supporting information files.

Code Availability Not applicable for the section.

Declarations

Conflict of interest No conflicts or competing interests exists.

References

1. Bengtsson BE. Cross-country skating: how it started. 2018. https://www.skiinghistory.org . Accessed 2 Mar 2018.
2. Bilodeau B, Roy B, Boulay MR. A comparison of three skating techniques and the diagonal stride on heart rate responses and speed in cross-country skiing. Int J Sports Med. 1991;12(1):71–6.
3. 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.
4. Boulay MR, Rundell KW, King DL. Effect of slope variation and skating technique on velocity in cross-country skiing. Med Sci Sports Exerc. 1994;27(2):281–7.
5. Carlsen CH, Rud B, Myklebust H, Losnegard T. Pole lengths influence O2-cost during double poling in highly trained cross-country skiers. Eur J Appl Physiol. 2018;118(2):271–81.
6. FIS. The International Ski Competition Rules (ICR: Book II Cross- Country) 2017. https://www.fis-ski.com/en/inside-fis/document-library/cross-country-documents. Accessed 7 May 2017.
7. Gløersen Ø, Kocbach J, Gilgien M. Tracking performance in endurance racing sports: evaluation of the accuracy offered by three commercial GNSS receivers aimed at the sports market. Front Physiol. 2018;9:1425.

8. Hansen E, Losnegard T. Pole length affects cross-country skiers' performance in an 80-m double poling trial performed on snow from standing start. Sports Eng. 2010;12(4):171–8.
9. Holmberg H-C, Lindinger S, Stöggl T, Eitzlmair E, Müller E. Biomechanical analysis of double poling in elite cross-country skiers. Med Sci Sports Exerc. 2005;37:807–18.
10. Ingjer F. Maximal oxygen uptake as a predictor of performance ability in women and men elite cross-country skiers. Scand J Med Sci Sports. 1991;1:25–30.
11. Kvamme B, Jakobsen V, Hetland S, Smith G. Ski skating technique and physiological responses across slopes and speeds. Eur J Appl Physiol. 2005;95(2–3):205–12.
12. Lindinger S, Stoeggl T, Mueller E. Biomechanical charateristics of further developed classical and skating techniques in cross-country skiing sprint competitions. J Biomech. 2006;39:S187–S187.
13. Losnegard T, Myklebust H, Skattebo Ø, Stadheim HK, Sandbakk Ø, Hallén J. The influence of pole length on performance, O2 cost, and kinematics in double poling. Int J Sports Physiol Perform. 2017;12(2):211–7.
14. 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.
15. 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):882–93.
16. Nilsson J, Jakobsen V, Tveit P, Eikrehagen O. Pole length and ground reaction forces during maximal double poling in skiing. Sport Biomech. 2003;2(2):227–36.
17. Onasch F, Killick A, Herzog W. Is there an optimal pole length for double poling in cross country skiing? J Appl Biomech. 2017;33(3):197–202.
18. Sandbakk Ø, Holmberg H-C. 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):1003–11.
19. 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.
20. Seeberg T, Tjønnås J, Rindal O, Haugnes P, Dalgard S, Sandbakk Ø. A multi-sensor system for automatic analysis of classical cross-country skiing techniques. Sports Eng. 2017;20(4):313–27.
21. Skattebo Ø, Losnegard T, Stadheim HK. Double poling physiology and kinematics of elite cross-country skiers: specialized long-distance versus all-round skiers. Int J Sports Physiol Perform. 2019;14:1199.
22. Smith G. Cross-country skiing: technique, equipment and environmental factors affecting performance. In: Zatsiorsky V, editor. Biomechanics in sport. IOC encyclopedia of sports medicine series. Oxford: Blackwell Science; 2000. pp. 247–70.
23. Solli GS, Kocbach J, Seeberg TM, Tjønnås J, Rindal OM, Haugnes P, Torvik P-Ø, Sandbakk Ø. 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.
24. Stöggl LT, Holmberg H-C. Force interaction and 3D pole movement in double poling. Scand J Med Sci Sports. 2011;21:e393–404.
25. Stöggl LT, Holmberg LH-C. Double-poling biomechanics of elite cross-country skiers: flat versus uphill terrain. Med Sci Sports Exerc. 2016;48(8):1580–9.
26. Stöggl T, Müller E, Lindinger S. Biomechanical comparison of the double-push technique and the conventional skate skiing technique in cross-country sprint skiing. J Sports Sci. 2008;26(11):1225–33.
27. Stöggl T, Holst A, Jonasson A, Andersson E, Wunsch T, Norström C, Holmberg HC. Automatic classification of the sub-techniques (gears) used in cross-country ski skating employing a mobile phone. Sensors. 2014;14(11):20589–601.
28. Tønnessen E, Haugen TA, Hem E, Leirstein S, Seiler S. Maximal aerobic capacity in the winter Olympic endurance disciplines: Olympic medal benchmarks for the time period 1990–2013. Int J Sports Physiol Perform. 2015;10(7):835–9.
29. Torvik P-Ø, Von Heimburg E, Sende T, Welde B. The effect of pole length on physiological and perceptual responses during G3 roller ski skating on uphill terrain. PLoS One. 2019;14:e0211550.
30. Trøen E, Rud B, Karlsson Ø, Carlsen CH, Gilgien M, Paulsen G, Tosterud OK, Losnegard T. Pole length's influence on performance during classic-style snow skiing in well-trained cross-country skiers. Int J Sports Physiol Perform. 2020;15(6):884.
31. Vandbakk K, Welde B, Kruken AH, Baumgart J, Ettema G, Karlsen T, Sandbakk Ø. Effects of upper-body sprint-interval training on strength and endurance capacities in female cross-country skiers. PLoS One. 2017;12(2):e0172706.

Study VI

frontiers
in Sports and Active Living

BRIEF RESEARCH REPORT
published: 22 April 2021
doi: 10.3389/fspor.2021.654864

Choice of Pole and Ski Lengths Among Elite Cross-Country Skiers: The Influence of Sex and Performance Level

Per-Øyvind Torvik[1]*, **Roland van den Tillaar**[1] **and Øyvind Sandbakk**[2]

[1] Department of Sports Sciences and Physical Education, Nord University, Levanger, Norway, [2] Department of Neuromedicine and Movement Science, Centre for Elite Sports Research, Faculty of Medicine and Health Sciences, Norwegian University of Science and Technology, Trondheim, Norway

Cross-country (XC) skiers employ whole-body exercise to generate speed through poles and skis. The choice of optimal pole and ski lengths are therefore of high importance. The aim of this study was to document pole and ski lengths among elite male and female cross-country skiers in the classical and skating styles and to investigate sex differences in body-height-normalized pole and ski lengths. Our secondary purpose was to correlate body-height-normalized pole and ski lengths with performance level within both sexes. In total, Norwegian men and women ($n = 87$ and 36, respectively), participating in the Norwegian XC championship 2020, were investigated. Most athletes used poles close to the length allowed by the International Ski Federation (FIS) in the classical style among both sexes, with men using slightly longer poles than women ($p < 0.05$). Body-height-normalized pole lengths in skating were similar in men and women (around 90% of body height). Women used relatively longer ski lengths than men in both styles ($p < 0.05$). Women showed moderate correlations ($r = 0.43$, $p < 0.05$) between body-height-normalized pole lengths and sprint performance. Male and female cross-country skiers use as long classical ski poles as possible within the current regulations, while they use skating poles similar to recommendations given by the industry. The fact that men use longer body-height-normalized poles than women, where there is a correlation between pole length and sprint performance, indicate that faster women are able to better utilize the potential of using longer poles when double-poling. However, while women use relatively longer skis than men, no correlation with performance occurred for any of the sexes.

Keywords: cross-country skiing, ski characteristics, pole characteristics, performance, gender differences, XC skiing

Edited by:
Jaime Fernandez Fernandez,
Universidad de León, Spain

Reviewed by:
Sarah J. Willis,
University of Lausanne, Switzerland
Kenji Doma,
James Cook University, Australia

****Correspondence:***
Per-Øyvind Torvik
per.o.torvik@nord.no

Specialty section:
This article was submitted to
Elite Sports and Performance
Enhancement,
a section of the journal
Frontiers in Sports and Active Living

Received: *17 January 2021*
Accepted: *17 March 2021*
Published: *22 April 2021*

Citation:
Torvik P-Ø, van den Tillaar R and
Sandbakk Ø (2021) Choice of Pole
and Ski Lengths Among Elite
Cross-Country Skiers: The Influence
of Sex and Performance Level.
Front. Sports Act. Living 3:654864.
doi: 10.3389/fspor.2021.654864

INTRODUCTION

Cross-country skiing is a winter endurance sport, performed while gliding over snow-covered hilly terrain using different sub-techniques of the classical and skating styles (Sandbakk and Holmberg, 2017). During this locomotion, skiers engage large muscle groups of the upper and lower limbs to generate and transfer power through poles and skis into the snow, thereby accelerating the center of mass forward (Holmberg, 2015). Consequently, an ongoing development of poles and skis aims to optimize this transfer of force, and at the same time, minimize energy dissipation through reduced friction and air drag. Accordingly, the development of performance in cross-country skiing is aided by concurrent improvements in skier capacity and equipment development (Pellegrini et al., 2018).

Although skis and poles are the main generators of propulsion in cross-country skiing, their characteristics are sparsely examined. However, harder ski tracks, better endurance-trained upper bodies of skiers (Stöggl and Holmberg, 2011), along with the introduction of sprint skiing and the professionalization of long-distance cross-country skiing have motivated skiers to experiment with longer pole lengths in the classical style. Indeed, several recent studies have indicated that double-poling can be done more effectively by employing longer poles (Losnegard et al., 2017a,b), with similar advantages recently found in skating (Torvik et al., 2019). In order to prevent skiers from using the double-poling technique exclusively in the classical style, the International Ski Federation (FIS) have limited pole lengths to <83% of body height while wearing ski boots (FIS, 2020). In skating, the standard pole recommendations are ∼20 cm below body height but FIS regulations do not allow poles to exceed an athlete's body height (FIS, 2020).

The guidelines for selecting ski lengths in classic and skating styles seem almost unchanged since the late 1980's, with typical recommendations being ∼10–15 cm and ∼25 cm above body height for skating and classic skis, respectively. While several previous studies have examined chamber height, ski stiffness, and grinding structures (Breitschädel, 2012), no studies have tested the effects of different ski lengths on performance in cross-country skiing. Breitschädel (2012) reported an average classical ski length in the Norwegian national team of 206 cm, with 8 cm shorter skis among women. That investigation did not evaluate ski length related to body height but reported an average of ∼20% longer nominal contact area (the ski length minus the kick wax area) between the ski and the snow among women (Breitschädel, 2012), indicating that women are using longer skis in relation to their body height.

Although some experimental studies have reported advantages of using longer poles in both the classical (Carlsen et al., 2018; Torvik et al., 2021a) and skating techniques (Torvik et al., 2019), no systematic report on elite skiers' employment of pole and ski lengths currently exists. In this context, possible sex and performance-level differences in body-height-normalized pole lengths are of high interest. Therefore, this study's primary purposes were to document pole and ski lengths among elite male and female cross-country skiers in the classical and skating styles and to investigate sex differences in body-height-normalized pole and ski lengths. Our secondary purpose was to correlate body-height-normalized pole and ski lengths with skiing performance within both sexes. Our main hypothesis was that men would use longer poles than women and that women would use longer skis, in both cases when poles or skis where normalized for body height.

TABLE 1 | Anthropometric, physiological and performance characteristics of the 87 male and 36 female Norwegian cross-country skiers participating in this study (Mean ± SD).

Variable	Male (n = 87)	Female (n = 36)
Age, yrs*	22.8 ± 2.7	24.1 ± 4.5
Body height, m	1.83 ± 0.06	1.68 ± 0.05
Body mass, kg	75.5 ± 6.3	59.9 ± 2.4
Body mass index, kg·m^{-2}	22.5 ± 3.1	21.2 ± 2.8
Maximum heart rate, beats·min^{-1}	198 ± 10	196 ± 8
VO_2max, L·min^{-1}	5.71 ± 0.5	3.95 ± 0.5
VO_2max, mL·min^{-1}·kg^{-1}	75.6 ± 4.7	65.8 ± 4.7
FIS points (distance)	95 ± 123	101.5 ± 59.8
FIS points (sprint)	93 ± 59	157 ± 105
Annual training volume, hours	666.5 ± 146.7	673.9 ± 146.2

**Age of participants in the 2019–2020 season. VO_{2max} – maximal oxygen uptake (highest self-reported value previous year). FIS, International Ski Federation.*

METHODS

Participants

Eighty-seven male and 36 female cross-country skiers who participated in the 2020 Norwegian Championships were included in this study. Inclusion criteria were that skiers competed in both the classical and skating styles, completed the questionnaire and systematically reported training in a diary. The level of male and female skiers was relatively evenly divided, from the best performers with 0 FIS points to the lowest-ranked skiers having 400 FIS points.

The Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for such studies. Therefore, the ethics of the study was carried out according to the institutional requirements and approval for data security was obtained from the Norwegian Centre for Research Data. Prior to the data collection, all participants provided written and informed consent to take part in the study voluntarily. The participants were informed that they could withdraw from the study at any time without providing a reason for doing so. The characteristics of the participants are presented in **Table 1**.

Questionnaire

Data was collected via an online questionnaire (Nettskjema: https://nettskjema.no/) in which the athletes self-reported their anthropometric, physiological, and training characteristics, in addition to ski and pole length in classic and skating styles. The questionnaire was designed to take 7–10 min to complete and contained 13 questions: 12 questions asking for a numeric value and one open-ended question. A pilot study was organized among 40 skiers (19–23 years old men and women) to ensure that participants understood all questions. Based on feedback from this pilot, a minor revision was carried out to ensure valid information. The online questionnaire was distributed to 156 male and 71 female participants through Facebook Messenger,

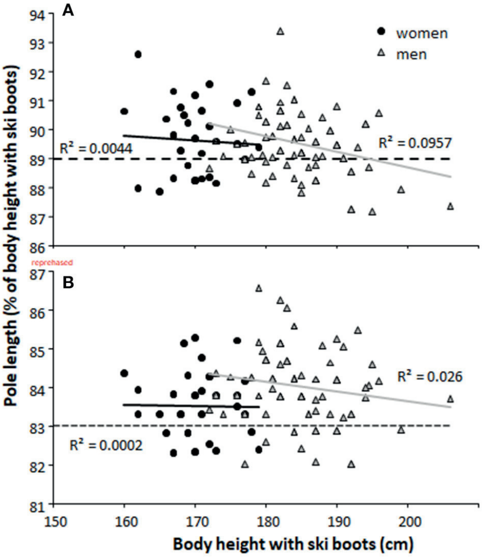


FIGURE 1 | Pole length in percentage of body height (using ski boots) for men and women in the **(A)** skating and **(B)** classical cross-country skiing techniques. - - indicates recommendation of pole length (89%) of the ski factory = = indicates the limit of pole length (83%) according to the FIS rules in classical ski technique.

based on the result list from the National Championships 10 and 15 km individual time trials for women and men, respectively.

The participants were asked to report their pole and ski lengths for the classical and skating techniques according to the equipment's length description. It is also essential to notice that the competition organizers have regular controls for pole length violations (i.e., <83% of body height in classic), and the current study participants did not have any violations of this rule although many subjects reported classical pole lengths slightly above the 83% rule of the FIS (rule 343.8.2). This is caused by the way poles are measured: "from the bottom of the pole, and to the highest attachment on the strap," while "body height is measured with ski boots on." Thereby, there is a 3–4 cm difference in pole length between the length provided by the producer and the pole measurements taken to control for competition regulations. Confirmations from representants for the most important ski factories are the basis for the recommendations on ski length in this manuscript.

Statistics

Questionnaire responses were summarized in numerical values to facilitate statistical analyses. Descriptive data for variables were recorded as means (SD. The Shapiro–Wilk test and standard visual inspection were used to examine the assumption of normality. To compare body-height-normalized pole and ski length between men and women, an independent samples *t*-test was used, while Pearson correlations were used to quantify the association between performance (FIS points), body-height-normalized pole and ski lengths. The threshold for interpretation of these correlations was: trivial (<0.1); small (0.1–0.3); moderate (0.3–0.5); high (0.5–0.7); very high (0.7–0.9); or practically perfect (0.9) (Calkins, 2005). The significance level was set at $p \leq 0.05$ for all tests, and the analyses were carried out using SPSS Statistics v27 (SPSS Inc., Chicago, IL, USA).

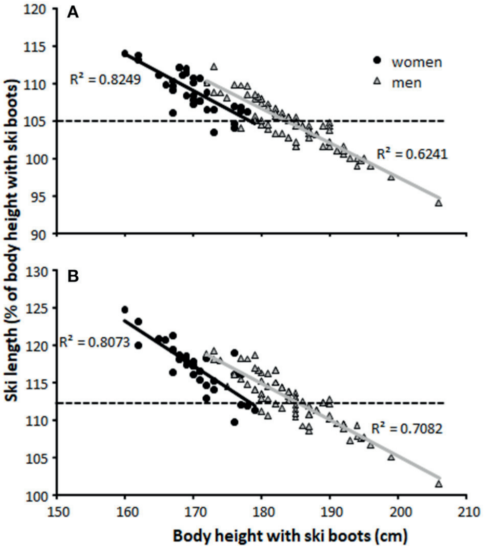


FIGURE 2 | Ski length in relation to body height (using ski boots) for men and woman in the **(A)** skating and **(B)** classical cross-country skiing techniques. - - indicates recommendation of the ski factory.

RESULTS

The body-height-normalized pole lengths used in the classical technique (**Figure 1A**) were on average 83.9 ± 0.9% for all athletes. Men (84.0 ± 0.9%) used significantly ($p = 0.005$) longer poles relative to their body height than women (83.5 ± 0.9%). In the skating technique (**Figure 1B**), the corresponding pole lengths were 89.5 ± 1.1%. No significant differences ($p = 0.61$) in body-height-normalized pole lengths in skating was found between men and women. No significant correlations were found between body-height-normalized pole length and body height (**Figures 1A,B**).

For body-height-normalized ski lengths (**Figures 2A,B**), women (skating: 108.0 ± 2.8%, classical: 117.2 ± 3.2%) used significantly longer ski lengths than men (skating: 104.4 ± 3.0%, classical: 112.6 ± 3.3%). A very high to a practically perfect negative relationship was found between body-height-normalized ski length and body height (**Figures 2A,B**).

No significant correlation was found between body-height-normalized ski or pole lengths and sprint or distance FIS points (all $r \leq 0.17$, all $p \geq 0.055$) when all athletes' data were pooled. When analyzed within each gender, a moderate correlation between sprint FIS points and body-height-normalized pole length in both skating ($r = 0.36$, $p = 0.030$) and classical techniques ($r = 0.43$, $p = 0.008$) was found in women.

DISCUSSION

The purpose of this report was to document pole and ski lengths among elite male and female cross-country skiers in the classical and skating styles and to investigate sex and performance-level differences in body-height-normalized pole and ski lengths. The main findings were that: (1) most of the athletes used poles close to the length allowed by FIS in the classical style among both sexes, with men using slightly longer body-height-normalized poles than women; (2) body-height-normalized pole lengths in skating were similar in men and women, with the average pole length being approximately similar to that recommended by the industry (around 90% of body height); (3) women used relatively longer ski lengths than men in both styles, which was longer than recommended for women; and (4) only women showed moderate correlations between body-height-normalized pole lengths and performance (i.e., sprint FIS points), while no other correlations between ski and pole lengths and performance occurred.

Most of the skiers used poles close to the length allowed by the FIS in the classical style (83% of body height measured to the strap of the pole using ski boots) among both sexes, with men using slightly longer poles than women. The trend that national level skiers in Norway maximize their pole lengths in classic style underlines the importance of effective double-poling, where longer poles seem beneficial for classical skiing performance (Losnegard et al., 2017b). It appears that men are more aware of this advantage than women and have experienced that double-poling can be done more effectively with longer poles. However, the fact that there was a correlation between performance and pole length in female sprint skiing indicates that the best female sprint skiers also utilize this advantage.

Body-height-normalized pole lengths in skating were similar among men and women, with average lengths in line with the industry's recommendations (around 90% of body height). While 66 and 71% of the female and male skiers reported slightly longer poles than recommended (SWIX, 2020), 60% are within ± 1% of the recommended pole length and 99% within ± 2%. Accordingly, only 1% of skiers are using longer skating poles (92–94% of body height), which has been shown to have a potential benefit in previous research by improving work economy, treadmill and on-snow performance in the G3 sub-technique (Torvik et al., 2019, 2021b). However, the use of long poles has often been associated with the negative effect on skiing technique among coaches, such as adverse effects on the skiing rhythm, skiing with high shoulders, more tension in the muscles to lift the arms higher in the repositioning phase, slower repositioning of the poles, and increased air resistance. Whether these anecdotes really apply needs to be examined and systematic experimenting in both the classical and skating styles is required in order to find optimal lengths for individual skiers.

Women used relatively longer ski lengths than men in both styles, with women's skis being longer than typically recommended. Here, anecdotes from coaches and skiers are that longer skis glide better than shorter ones due to better weight distribution over a more extended nominal contact area, an advantage that is also confirmed in previous research (Breitschädel, 2012). Therefore, longer classical skis will be selected if they are soft enough to get sufficient grip. It is also known that the ski industry produces a smaller number of top skis for the smallest women, and female skiers as well as ambitious young boys and girls will therefore compete for the same pairs of skis within the recommended length for their body size. In such a case, choosing skis that are 5–10 cm longer enables higher number of top skis to choose from. This is also supported by communication with the ski industry, who argue that production of skis in different lengths is mainly dependent on financial reasonings (personal communication with Mobakken, 2021). In contrast, the tallest men are using skis close to the maximal ski length produced, since the longest classical and skating skis on the market are 207–210 and 190–195 cm, respectively. Accordingly, ∼80% of the male cross-country skiers use the maximal ski lengths in both styles.

Research Limitations and Future Recommendations

A main limitation of this investigation is the difference in pole length measurements defined by the FIS rules and the one used by the industry. This does not allow a direct comparison, but we have checked these differences for the most common pole types employed here. Along the same lines, normalizing for body height might not be an optimal procedure, since the anthropometric differences between athletes (e.g., differences in length of the head and the neck) may lead to differences in the rotation point of the shoulder between skiers with similar body height. In this context, the shoulder joint is the point of departure for transferring power from the body through the arms and to the poles. Previously, the shoulder height was a standard way to select both classical and skating poles (Bjerke, 2020), which still seems to be a more appropriate method than using body height. In future research, these aspects should be considered when discussing or analyzing pole lengths in cross-country skiing.

CONCLUSION

This study reports pole and ski lengths chosen by elite male and female cross-country skiers and examines sex and performance-level differences in this respect. It seems clear that the best-performing male as well as female cross-country skiers use as long of classic ski poles as possible within the current regulations, which is likely to optimize their double-poling performance. In general, men tend to choose poles that are closer to this limit than women, which might be explained by the greater use of double-poling than diagonal stride in men's compared to women's classical competitions. However, longer body-height-normalized pole lengths among faster women in sprint indicate that faster women are able to better utilize the potential of using longer poles when double-poling. In skating, similar body-height-normalized pole lengths are used by men and women, with lengths similar to those recommended by the industry. For skis, women used relatively longer ski lengths than men in both styles, which were also longer than recommended. Whether this is due to longer skis being advantageous or a bias with more good skis produced with lengths optimal for men by the industry needs further examination. However, no significant correlations between ski length and performance were found, with close to perfect correlations between body height and ski length, indicating that ski length was purely chosen by body height within both sexes.

DATA AVAILABILITY STATEMENT

The dataset presented in this article may be obtained by contacting the corresponding author. Requests to access these datasets should be directed to Per-Øyvind Torvik, per.o.torvik@nord.no.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

P-ØT and ØS designed the study. P-ØT performed data collection and wrote the first draft of the manuscript. RT performed the statistical analyses. P-ØT, RT, and ØS contributed to interpretation of the results. RT and ØS contributed to write the final manuscript. All authors read and accepted the final version of the manuscript.

ACKNOWLEDGMENTS

We thank Magnus Sivertsen for performing a pilot test preceding this study and all the skiers for their participation.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2021.654864/full#supplementary-material

REFERENCES

Bjerke, H. (2020). "Technician SWIX," ed P.-Ø. Torvik (Lillehammer).

Breitschädel, F. (2012). Variation of Nordic classic ski characteristics from Norwegian national team athletes. *Proc. Eng.* 34, 391–396. doi: 10.1016/j.proeng.2012.04.067

Calkins, K. G. (2005). *Applied Statistics: More Correlation Coefficients*. Available online at: http://www.andrews.edu/~calkins/math/edrm611/edrm13.htm (accessed November 29, 2006).

Carlsen, C. H., Rud, B., Myklebust, H., and Losnegard, T. (2018). Pole lengths influence O_2-cost during double poling in highly trained cross-country skiers. *Eur. J. Appl. Physiol.* 118, 271–281. doi: 10.1007/s00421-017-3767-x

FIS, F. I. D. S. (2020). *Rules*. Available online at: https://www.fis-ski.com/en/inside-fis/document-library/cross-country-documents (accessed August 04, 2020).

Holmberg, H.-C. (2015). The elite cross-country skier provides unique insights into human exercise physiology. *Scand. J. Med. Sci. Sports* 25:100. doi: 10.1111/sms.12601

Losnegard, T., Myklebust, H., Ehrhardt, A., and Hallén, J. (2017a). Kinematical analysis of the V2 ski skating technique: a longitudinal study. *J. Sports Sci.* 35, 1219–1227. doi: 10.1080/02640414.2016.1218036

Losnegard, T., Myklebust, H., Skattebo, Ø., Stadheim, H. K., Sandbakk, Ø., and Hallén, J. (2017b). The influence of pole length on performance, O_2 cost, and kinematics in double poling. *Int. J. Sports Physiol. Perform* 12, 211–217. doi: 10.1123/ijspp.2015-0754

Pellegrini, B., Stöggl, T. L., and Holmberg, H.-C. (2018). Developments in the biomechanics and equipment of olympic cross-country skiers. *Front. Physiol.* 9:976. doi: 10.3389/fphys.2018.00976

Sandbakk, Ø., and Holmberg, H.-C. (2017). Physiological capacity and training routines of elite cross-country skiers: approaching the upper limits of human endurance. *Int. J. Sports Physiol. Perform* 12, 1003–1011. doi: 10.1123/ijspp.2016-0749

Stöggl, L. T., and Holmberg, H.-C. (2011). Force interaction and 3D pole movement in double poling. *Scand. J. Med. Sci. Sports* 21, e393–e404. doi: 10.1111/j.1600-0838.2011.01324.x

SWIX (2020). Available online at: https://www.swixsport.com/no/tips/finn-din-storrelse/staver/ (accessed January 13, 2021).

Torvik, P.-Ø., Persson, J., and van den Tillaar, R. (2021a). The effects of sub-technique and pole length on classic roller skiing performance and physiological responses at steep uphill inclination. *J. Hum. Kinet.* 77, 97–105. doi: 10.2478/hukin-2021-0014

Torvik, P.-Ø., van den Tillaar, R., Bostad, G., and Sandbakk, Ø. (2021b). The effect of increased pole length on performance during an on-snow cross-country skating competition for women. *J. Sci. Sport Exer*.

Torvik, P.-Ø., von Heimburg, E., Sende, T., and Welde, B. (2019). The effect of pole length on physiological and perceptual responses during G3 roller ski skating on uphill terrain. *PLoS ONE* 14:e0211550. doi: 10.1371/journal.pone.0211550

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.

This article-based thesis consists of an extended abstract and six articles.

Accordingly, the training routines for the development of performance in XC skiing are aided by concurrent improvements in the skier's physiological capacity, skiing technique and pole length manipulations. A consequence of the different competition formats and distances is more specialized training to develop cross-country skiers' performance by specializing in sprint, distance in the Olympic and long-distance disciplines. Furthermore, pole length manipulations may have enhanced performance in both Olympic distance and long-distance skiers. This thesis aims to examine training characteristics and pole length manipulation for optimizing performance and associated physiological and kinematic capacities in long-distance and Olympic-distance XC skiing.

Study I-II - aimed to compare training characteristics, physiological capacities, and kinematical patterns in DP between Olympic distance and long-distance XC skiers. Here, study I found the highest ever reported DP/RUN-VO_{2peak} ratio of 97% in LDS, which coincided with better DP performance and ability to maintain effective technique at faster DP speeds. In addition, LDS achieved higher GE than ODS and demonstrated longer relative poling times and lower normalized EMG amplitudes in rectus abdominis and biceps femoris. Taken together, the combination of better DP-specific aerobic energy delivery capacity, efficiency and technical solutions that lead to the superior DP performance found among specialized LDS are reflected in their training patterns with a notable focus on DP training specifically for long-distance events.

Study III-VI - aimed to describe choice of pole length by competitive XC skiers and investigate the effects of pole length manipulation on performance in classical and skating style XC skiing. All studies showed longer poles to be superior to self-selected and/or shorter poles, both in DP (study III) and G3 skating (study IV) when roller skiing and when ski skating on snow (study V). Performance benefits of increased pole length seem to be greatest in uphills, and associated with altered kinematics, reduced vertical displacement of CoM and reduced oxygen cost.

NORD
University

ISBN: 978-82-93196-55-6
Print: Trykkeriet, Nord University
www.nord.no