Doctoral theses at NTNU, 2022:275

Camilla Høivik Carlsen

Performance and Performance-Determining Factors for Paralympic Cross-Country Skiing

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement
Science

NTNU
Norwegian University of
Science and Technology

Camilla Høivik Carlsen

Performance and Performance-Determining Factors for Paralympic Cross-Country Skiing

Thesis for the Degree of Philosophiae Doctor

Trondheim, September 2022

Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the Degree of Philosophiae Doctor

Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

ISBN 978-82-326-6343-9 (printed ver.)
ISBN 978-82-326-5453-6 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

Doctoral theses at NTNU, 2022:275

Printed by NTNU Grafisk senter

Avhandlingens tittel på norsk:
«Prestasjon og prestasjonsbestemmende faktorer i Paralympisk langrenn»

Kort og beskrivende populærvitenskapelig tittel (på norsk):
«Prestasjonsbestemmende faktorer i Paralympisk langrenn»

I eliteidrett er det kunnskap som er uunnværlig for å nå toppnivå, så som de spesifikke arbeidskravene i den enkelte idrett og hvordan de prestasjonsbestemmende faktorene virker på prestasjonen. I utholdenhetsidrett er informasjon om hvor og hvordan en utøvers prestasjon kan forbedres for å vinne en konkurranse også interessant. Sammenlignet med funksjonsfriske langrennsløpere, kan prestasjonen bli påvirket av de ulike funksjonsnedsettelsene til Paralympiske (Para) langrennsløpere (dvs., bevegelseshemmede sittende, bevegelseshemmede stående og synshemmede stående (svaksynt og blinde)). Jeg har i denne avhandlingen kombinert tre studier og dermed undersøkt forskjeller i konkurransetid og prestasjonsbestemmende faktorer i Para langrenn. Først ble historiske konkurransedata analysert for å skape et overblikk over prestasjonene til Para og funksjonsfriske langrennsløpere i perioden mellom 2011 til 2020 (Studie I). Dernest ble anvendeligheten til et rammeverk basert på mikro-sensor teknologi evaluert for avanserte prestasjonsanalyser i feltet (Studie II). De fysiologiske og biomekaniske prestasjonsbestemmende faktorer påvirker prestasjonen under konkurranse, men undersøkelse av disse utendørs er krevende. Derfor ble de prestasjonsbestemmende faktorer undersøkt for sittende staking i to stigninger tilsvarende flat terreng og motbakke på en rulleskimølle (Studie III).

Hovedfunnene fra avhandlingen viste at Para langrennsløpere hadde sammenlignet med funksjonsfriske langrennsløpere større forskjeller i konkurransetid, som sannsynligvis ble skapt av funksjonsnedsettelsenes effekt på prestasjonen, samt et lavere antall konkurrenter (Studie I). Videre, hvor og hvorfor forskjellene i konkurransetid oppstår kan undersøkes i detalj ved å benytte det evaluerte rammeverket. Bruken av et slikt rammeverk anbefales til fremtidige undersøkelser av prestasjonen til Para langrennsløpere (Studie II). Undersøkelsen av sittende staking demonstrerte at det ble skapt en høyere arbeidsrate ved bruk av en lengre stakefase og energien ble brukt mer effektivt i motbakke enn i flatt terreng. Dette indikerer fordelene av en lavere hastighet ved sittende staking i motbakke, som resulterer i en mer effektiv teknikk, hvor en større andel av energien går til arbeide (Studie III). Dette kan sannsynligvis forklare hvorfor langrennsløpere finner det gunstig å ha en større intensitetsøkning i motbakke enn i flatt terreng.

Navn kandidat: Camilla Høivik Carlsen
Institutt: Institutt for nevromedisin og bevegelsesvitenskap
Veileder(e): Prof. Øyvind Sandbakk og Dr. Julia Kathrin Baumgart
Finansieringskilde: Institutt for nevromedisin og bevegelsesvitenskap

Ovennevnte avhandling er funnet verdig til å forsvares offentlig for graden Philosophia Doctor (PhD i "program", Doctor Philosophiae). *Disputas finner sted i Granåsen konferansesenter d. 27 sep., kl. 12.15*

SUMMARY

An understanding of sport-specific performance demands and the role of performance-determining factors, as well as information on where and how an athlete's performance can be improved sufficiently to win a competition are imperative in elite sports. In Paralympic (Para) cross-country skiing, such information can be obtained by combining the results of analyses of historical race data with the results of advanced in-field performance analyses. Subsequently, deeper insights into the complex factors determining performance and the associated technical and tactical aspects in Para cross-country skiing can be obtained in the laboratory. Differently from able-bodied skiers, Para skiers' different impairments can affect performances between Para skiers (i.e., physically impaired sitting skiers, physically impaired standing skiers, and visually impaired standing skiers).

The overall aim of this thesis is to investigate differences in race times and performance-determining factors in Para cross-country skiing through three interconnected studies: a study in which analyses of historical race data provided an overview of Para cross-country skiing performance (Study I); a study involving a case series to evaluate the feasibility of a framework for analyses of advanced in-field Para cross-country skiing performance (Study II); an experimental study that investigated specific physiological and biomechanical performance-determining factors in sitting skiing (sit-skiing) (Study III).

In Study I, differences in race time (i.e., the average percent difference in race time for each skier compared with the winner, RT_{diffs}) were compared for the top 3 and top 8 female and male Para and able-bodied skiers. This was done through analysis of race data from World Cups, World Championships, and Paralympic/Olympic Winter Games in the 2011-2020 seasons (10 seasons in total). Thereafter, in Study II, to examine in more depth Para cross-country skiing performance and what happens during competitions, the feasibility of employing a framework based on micro-sensor technology for in-field analyses was evaluated during a classical cross-country skiing race on snow. For that purpose, data from a global navigation satellite system (GNSS) and an inertial measurement unit (IMU) were integrated to compare descriptively time loss and sub-technique selection as a function of speed between elite Para skiers with a standing skiing posture and able-bodied skiers (three Para and seven able-bodied, respectively) (Study II). Furthermore, physiological and biomechanical factors affect performance outcome during a race, but investigation of these factors outdoors is challenging. Performance-determining factors are well established from research on able-bodied cross-country skiers, but are less known for sitting skiers. In Study III the performance-determining factors were investigated for upper-body double poling in flat and uphill sit-skiing on a treadmill. Fifteen able-bodied skiers completed two test sessions that were counterbalanced by the incline 0.5% (FLAT) or 5% (UPHILL), each comprising four submaximal stages, an incremental test to exhaustion, and a verification test. Peak work rate (WR_{peak}) and peak oxygen uptake ($\dot{V}O_{2peak}$), as well as other physiological variables, rating of perceived exertion (RPE), gross efficiency (GE), and cycle characteristics at identical submaximal work rates were compared between FLAT and UPHILL (Study III).

The main findings in Study I were that Para skiers displayed larger RT_{diffs} than able-bodied skiers (top 3: 2.1% vs. 0.9%; top 8: 6.2% vs. 2.1%, all $p < 0.01$), and female skiers displayed larger RT_{diffs} than male skiers (top 3: 1.8% vs. 1.3%; top 8: 4.9% vs. 3.5%, all $p < 0.05$). In Study II, the descriptive comparison revealed that compared with the female and male able-bodied skiers, the female and male Para skiers displayed a 14% and 19% slower average speed, respectively, with the largest time loss in uphill terrain. Furthermore, at lower speed ranges, the female Para/able-bodied skiers selected on average double poling, double poling with a kick, and diagonal stride for 60/43%, 15/10%, and 25/47% of the distance, respectively, while the corresponding numbers for male Para/able-bodied skiers were 58/18%, 1/13%, and 40/69%. At higher speed ranges, the female Para/able-bodied skiers selected on average double poling and tuck position for 26/52% and 74/48% of the distance, respectively, while the corresponding percentages for male Para/able-bodied skiers were 29/66% and 71/34% (Study II). In Study III, when sit-skiing, the WR_{peak} was 35% higher for UPHILL compared with FLAT ($p < 0.001$), and there was more work per cycle (UPHILL: 170 ± 23 J vs. FLAT: 113 ± 22 J, $p < 0.001$) and twice as long poling time (UPHILL: 0.4 ± 0.06 s vs. FLAT: 0.2 ± 0.04 s, $p < 0.001$). However, the peak physiological variables and RPE did not display any significant differences between UPHILL and FLAT (all $p > 0.3$). When sit-skiing at identical submaximal work rates, GE was 0.5–2 percentage points lower for FLAT compared with UPHILL ($p < 0.001$) (Study III).

Overall, this thesis shows that Para skiers had larger RT_{diffs} than able-bodied skiers (Study I), which probably can be attributed disability-related differences in performance and fewer competitors. Furthermore, the larger RT_{diffs} displayed by the female skiers than by their male counterparts might have been due to the lower performance levels of the female skiers (Study I). Furthermore, where and why the differences in race times occur during a race can be investigated by using the framework proposed in Study II. The framework was evaluated as feasible since, with high-accuracy positioning and IMU measurements, and validated algorithms, it achieved an automatic sub-technique classification accuracy of ~86% and ~96% for the Para and able-bodied skiers, respectively. Thus, it is recommended that such a framework should be employed in future large-scale investigations of cross-country skiing performance (Study II). Furthermore, in Study III, the investigations of the performance-determining factors demonstrated that a higher WR_{peak} was achieved during uphill sit-skiing compared with flat sit-skiing. The higher WR_{peak} was achieved through longer poling times that allowed more work per cycle and better GE. Together, the results indicate the advantage of the lower speed when sit-skiing uphill, which allow a more efficient technique with a larger proportion of the metabolic energy going to produce work (Study III). This probably explains why skiers find it useful to increase their efforts in uphill terrain during competitions.

Overall, this thesis shows larger RT_{diffs} among Para skiers than able-bodied skiers (Study I), and it evaluates a framework based on micro-sensor technology as feasible for investigating where and why differences in race times occur (Study II). Furthermore, the thesis shows that higher WR_{peak} and better efficiency are achieved when sit-skiing in uphill terrain compared with in flat terrain (Study III).

SUMMARY IN NORWEGIAN

Kunnskap om de idretts-spesifikke arbeidskravene og virkningen av de prestasjonsbestemmende faktorene, samt informasjon om hvor og hvordan en utøvers prestasjon kan forbedres for å vinne en konkurranse, er uunnværlig i eliteidrett. I Paralympisk (Para) langrenn vil slik informasjon kunne oppnås ved å kombinere analyser av historiske konkurransedata og avanserte prestasjonsanalyser under konkurranse. Deretter kan det skapes en bedre forståelse av de prestasjonsbestemmende faktorene og forbindelsen til det tekniske- og taktiske aspektet ved testing i laboratoriet. Sammenlignet med funksjonsfriske langrennsløpere, kan prestasjonen også bli påvirket av de ulike funksjonsnedsettelsene til Para langrennsløperne (dvs., bevegelseshemmede sittende, bevegelseshemmede stående og synshemmede stående (svaksynt og blinde)).

Målet med denne avhandlingen var derfor å undersøke forskjeller i konkurransetid og prestasjonsbestemmende faktorer i Para langrenn ved å kombinere tre studier. En studie analyserte historiske konkurransedata og skapte et overblikk over prestasjonene til Para langrennsløpere (Studie I). En kasus-kontrollstudie evaluerte anvendeligheten til et rammeverk for avanserte prestasjonsanalyser i feltet (Studie II). En eksperimentell studie som undersøkte spesifikke fysiologiske og biomekaniske prestasjonsbestemmende faktorer av sittende staking (Studie III).

I Studie I ble forskjeller i konkurransetid (dvs., den gjennomsnittlige prosentvise forskjell i konkurransetid for hver langrennsløper sammenlignet med vinneren, RT_{diffs}) sammenlignet mellom topp 3 og topp 8 kvinnelige og mannlige Para og funksjonsfriske langrennsløpere. Dette ble gjort ved å analysere konkurransedata fra Verdens Cup, Verdensmesterskap og Paralympiske/Olympiske vinterleker i perioden mellom 2011 til 2020. Deretter, for i Studie II å analysere prestasjonen til Para langrennsløpere i en konkurransesituasjon nærmere, ble anvendeligheten av et rammeverk basert på mikro-sensor teknologi, undersøkt under et klassisk skirenn. Dette ble gjort ved å integrere data fra et satellittbasert system for navigasjon og posisjonering (GNSS), samt en treghetsmåleenhet (IMU), og deskriptivt sammenligne tidstapet og valg av delteknikk ved en gitt hastighet mellom elite Para og funksjonsfriske langrennsløpere (Studie II). Under konkurranse vil fysiologiske og biomekaniske prestasjonsbestemmende faktorer påvirke prestasjonen, men undersøkelse av disse utendørs er krevende. Med de prestasjonsbestemmende faktorer godt etablert for funksjonsfriske langrennsløpere, er det mindre kunnskap for sittende langrennsløpere. I Studie III ble derfor de prestasjonsbestemmende faktorene undersøkt for sittende staking i to stigninger på en rulleskimølle. Femten funksjonsfriske langrennsløpere fulførte to økter, en med 0.5% stigning (FLAT) og en med 5% stigning (MOTBAKKE) i en randomisert rekkefølge. Hver økt besto av fire submaksimale drag, en inkrementell test til utmattelse og en verifiseringstest. Peak arbeidsrate (WR_{peak}) og peak oksygenopptak ($\dot{V}O_{2peak}$), samt en rekke andre fysiologiske variabler, opplevd anstrengelse (RPE), effektivitet (GE) og sykluskarakteristikker ble sammenlignet mellom FLAT og MOTBAKKE (Studie III).

I Studie I var RT_{diffs} større for Para enn for de funksjonsfriske langrennsløperne (topp 3: 2.1% vs. 0.9%; topp 8: 6.2% vs. 2.1%, alle $p < 0.01$), samt at de kvinnelige langrennsløperne hadde større RT_{diffs} enn de mannlige (topp 3: 1.8% vs. 1.3%; topp 8: 4.9% vs. 3.5%, alle $p < 0.05$). I Studie II, sammenlignet med de funksjonsfriske langrennsløperne av samme kjønn, hadde de kvinnelige og mannlige Para langrennsløperne henholdsvis en 14% og 19% lavere gjennomsnittshastighet, samt det største tidstapet i motbakke. I tillegg benyttet de kvinnelige Para/funksjonsfriske langrennsløperne i gjennomsnitt staking, dobbelttak med fraspark og diagonalgang henholdsvis 60/43%, 15/10% og 25/47% av distansen ved lavere hastigheter, hvor de mannlige Para/funksjonsfriske langrennsløperne benyttet disse teknikkene 58/18%, 1/13% og 40/69% av distansen. Ved høyere hastigheter benyttet de kvinnelige Para/funksjonsfriske langrennsløperne i gjennomsnitt staking og en «hockey» posisjon henholdsvis 26/52% og 74/48% av distansen, hvor de mannlige Para/funksjonsfriske langrennsløperne benyttet delteknikkene 29/66% og 71/34% av distansen (Studie II). I Studie III, ble det ved sittende staking oppnådd en 35% høyere WR_{peak} i MOTBAKKE enn i FLAT ($p < 0.001$), samt utførte de et større arbeid i hver syklus (MOTBAKKE: 170 ± 23 J vs. FLAT: 113 ± 22 J, $p < 0.001$) og dobbelt så lang stakefase (MOTBAKKE: 0.4 ± 0.06 s vs. FLAT: 0.2 ± 0.04 s, $p < 0.001$). Imidlertid var det ikke noen forskjell i peak verdiene av de fysiologiske variablene og RPE mellom MOTBAKKE og FLAT (alle $p > 0.3$). Derimot, ved like submaksimale arbeidsrater var GE 0.5-2 prosentpoeng lavere i FLAT enn i MOTBAKKE ($p < 0.001$) (Studie III).

Oppsummert viser avhandlingen, at den større RT_{diffs} til Para sammenlignet med funksjonsfriske langrennsløpere (Studie I), sannsynligvis ble skapt av funksjonsnedsettelsenes effekt på prestasjonen, samt et lavere antall konkurrenter. I tillegg hadde de kvinnelige langrennsløperne sannsynligvis større RT_{diffs} grunnet et lavere prestasjonsnivå enn de mannlige langrennsløperne (Studie I). Videre, hvor og hvorfor forskjellene i konkurransetid oppstår kan undersøkes i detalj ved å benytte rammeverket presentert i Studie II. Rammeverket var evaluert anvendelig, da det ved bruk av presise posisjons- og IMU målinger, samt validerte algoritmer, hadde en automatisk delteknikk-klassifisering på 86% og 96% for henholdsvis Para og funksjonsfriske langrennsløpere. Herved er bruken av et slikt rammeverk anbefalt til fremtidige undersøkelser av prestasjonen til Para langrennsløpere (Studie II). Videre, ble det i Studie III, fra undersøkelsen av de prestasjonsbestemmende faktorene, demonstrert en høyere WR_{peak} ved sittende staking i motbakke enn i flatt terreng. Den høyere WR_{peak} ble skapt av en lengre stakefase med et større arbeid i hver syklus og bedre GE. Dette indikerer fordelene av den lavere hastigheten ved sittende staking i motbakke, som resulterer i en mer effektiv teknikk, hvor en større andel av energien går til arbeide (Studie III). Dette kan sannsynligvis forklare hvorfor langrennsløpere finner det gunstig å ha en større intensitetsøkning i motbakke enn i flatt terreng.

Denne avhandlingen viser en større RT_{diffs} til Para sammenlignet med funksjonsfriske langrennsløpere (Studie I), samt at den evaluerte et rammeverk basert på mikro-sensor teknologi som er anvendelig for undersøkelse av hvor og hvorfor forskjellene i konkurransetid skapes under konkurranse (Studie II). Videre viste avhandlingen at det ble oppnådd en høyere WR og bedre effektivitet ved sitting staking i motbakke enn i flat terreng (Studie III).

ACKNOWLEDGEMENTS

This thesis is the result of three years of new discoveries both scientifically and personally. I am grateful to the people who gave me this opportunity, believed in me, and have helped me along the way. Therefore, I would like to take this opportunity to give a special thanks to:

My main supervisor, Professor Øyvind Sandbakk, you have guided, challenged, supported, and motivated me with an inexhaustible commitment and engagement from the beginning to the end of this PhD. You have a special ability to see the people around you and adapt your supervision and guiding. Thank you for seeing me and helping me grow personally and professionally.

My co-supervisor, Dr. Julia Kathrin Baumgart, you have an incredible engagement and positivity around you, it is inspiring. Thank you for all you have taught me, from English grammar to making smashing power point presentations. Your knowledge and passion for Para sports is remarkable and has been a large motivation for me. I am thankful for the way you have guided and supported me through this PhD.

My co-authors, David McGhie for hours in the laboratory, Jan Kocbach for introducing me to a fascinating technological world, Evy Paulussen for an interesting data collecting of elite Para skiers, Pål Haugnes and Cecilia Severin for constructive comments and engagement.

All the people at SenTIF and of Olympiatoppen, Mid-Norway, for creating a positive work environment and increasing my knowledge of human performance beyond the scope of this thesis.

My friends and family, especially my mom and dad for always being there with support and love. My grandmother and Peder Martin for celebrating the small and big victories in everyday life here in Trondheim and supporting hugs when needed.

My dear Martin, for believing in me, for keeping me going, and giving me a life beyond this academic world. Thanks for being you!

LIST OF PUBLICATIONS

This thesis combines the following articles, which in turn are based on research conducted in separate studies that are referred to as Studies I-III in the text. The articles are provided at the end of this thesis with permission from the publishers. The thesis also includes unpublished results based on the additional data from the three studies.

I. Carlsen CH, Severin C, Sandbakk Ø, Baumgart JK. Comparison of Race Time-differences between and within Para and Able-Bodied Cross-Country Skiers. *Front. Sports Act. Living* (2022) *3:* Article *823014.* doi: 10.3389/fspor.2021.823014

II. Carlsen CH, Baumgart JK, Kocbach J, Haugnes P, Paulussen EMB, Sandbakk Ø. Framework for In-Field Analyses of Performance and Sub-Technique Selection in Standing Para Cross-Country Skiers. *Sensors* (2021) 21: Article 4876. doi: 10.3390/s21144876

III. Carlsen CH, McGhie D, Baumgart JK, Sandbakk Ø. Comparison of Physiological and Biomechanical Responses to Flat and Uphill Cross-Country Sit-Skiing in Able-Bodied Athletes. *Int J Sports Physiol Perform* (2021) 16(11), 1596–1602. doi: 10.1123/ijspp.2020-0752

ABBREVIATIONS AND FREQUENTLY USED PHRASES

AB	Able-bodied
B1-3	Blind sports, classes for visually impaired standing skiers
BLa	Blood lactate concentration [mmol·L^{-1}]
BLa_{peak}	Peak blood lactate concentration [mmol·L^{-1}]
Category	Classification of Para skiers based on their disability
Classes	Division of skiers within a category, based on the functional impact of their disability on their performance
CL	Cycle length [m]
CR	Cycle rate [Hz]
CT	Cycle time [s]
DIA	Diagonal stride, sub-technique within the classical skiing technique
DK	Double poling with a kick, sub-technique within the classical skiing technique
DP	Double poling, sub-technique within the classical skiing technique
FLAT	Condition during cross-country sit-skiing, 0.5% incline and submaximal speeds 10, 12, 14, and 16 km·h^{-1} (Study III)
FIS	The International Ski Federation
GE	Gross efficiency [%]
GNSS	Global navigation satellite systems
HRB	Herringbone, sub-technique within the classical skiing technique
HR	Heart rate [beats·min^{-1}]
HR_{peak}	Peak heart rate [beats·min^{-1}]
IMU	Inertial measurement unit
IPC	The International Paralympic Committee
LT	Lactate threshold
LPS	Local positioning system
LW2-9	Locomotor Winter, classes for physically impaired standing skiers
LW10-12	Locomotor Winter, classes for physically impaired sitting skiers
MR	Metabolic rate [W]
MR_{peak}	Peak metabolic rate [W]
OTHER	Turn techniques and cycles that do not fulfil specified criteria for DIA, DK, and DP (Study II)
OWG	Olympic Winter Games
Para	Paralympic

PT	Poling time [s]
PWG	Paralympic Winter Games
RER	Respiratory exchange ratio
RER_{peak}	Peak respiratory exchange ratio
RPE	Rating of perceived exertion [Borg scale, 6-20]
RPE_{peak}	Peak rating of perceived exertion [Borg scale, 6-20]
RT_{diffs}	Differences in race times [%]
RPE_M	Rating of perceived muscular exertion [Borg scale, 6-20]
RPE_V	Rating of perceived ventilatory exertion [Borg scale, 6-20]
RTK	Real-Time Kinematic
SD	Standard deviation
Sitting skiers	Physically impaired sitting skiers
Skiers	Cross-country skiers
Standing skiers	Physically impaired standing skiers
ST	Swing time [s]
Time factor	Percentage used to calculate the adjusted race time and overall ranking
Tuck	Tucked position, sub-technique within the classical and freestyle skiing technique
UPHILL	Condition during cross-country sit-skiing, 5% incline and submaximal speeds 4, 5, 6, and 7 $km \cdot h^{-1}$ (Study III)
VE	Minute ventilation [$L \cdot min^{-1}$]
VE_{peak}	Peak minute ventilation [$L \cdot min^{-1}$]
VI skiers	Visually impaired standing skiers
V1	Padling, sub-technique within the freestyle skiing technique
V2	Double dance, sub-technique within the freestyle skiing technique
V2a	Single dance, sub-technique within the freestyle skiing technique
$\dot{V}O_2$	Oxygen uptake [$mL^{-1} \cdot kg^{-1} \cdot min^{-1}$]
$\dot{V}O_{2max}$	Maximal oxygen uptake [$mL^{-1} \cdot kg^{-1} \cdot min^{-1}$]
$\dot{V}O_{2peak}$	Peak oxygen uptake [$mL^{-1} \cdot kg^{-1} \cdot min^{-1}$]
$Work_{cycle}$	Work per cycle (J)
WR	Work rate, the amount of energy expended (W)
WR_{peak}	Peak work rate (W)

TABLE OF CONTENTS

1 BACKGROUND

1.1 HISTORY OF PARA CROSS-COUNTRY SKIING

The origin of Para cross-country skiing in Europe dates back to the late 1940s. The first organization for Para cross-country skiing was a ski school for amputees, which was established in Austria in 1950. During the 1960s different organizations for people with visual impairments were established.[1, 2] In 1976 the first Paralympic Winter Games (PWG) were hosted in Örnsköldsvik, Sweden, for athletes with amputations and visually impairments (VI).[1-4] In the second PWG, held in Geilo, Norway in 1980, athletes with spinal cord injury (SCI) were allowed to compete, and at the third PWG, held at Innsbruck, Austria, in 1984, athletes with cerebral palsy (CP) and other movement-related impairments (les autres) were allowed to compete.[2] In the case of Para cross-country skiing, the number of participating countries at the PWG doubled from 15 in the first PWG held in Örnsköldsvik (1976) to 31 in the twelfth PWG held in Pyeongchang, 2018,[4] and the number of competing skiers has varied over the years (Figure 1).

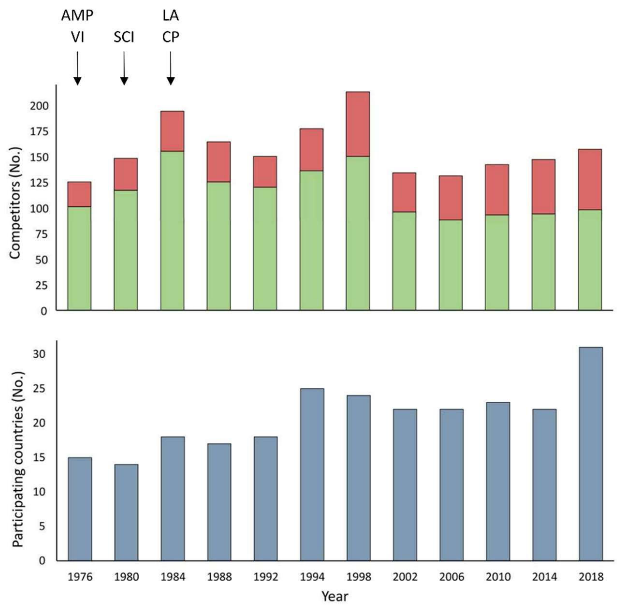


Figure 1. The number of competitors (female skiers (red), male skiers (green)), and countries (blue) for Para cross-country skiing in the Paralympic Winter Games (PWG) between 1976 and 2018. The black arrows indicate the year that type of disabilities participated at the PWG for the first time. Amputation (AMP); Cerebral palsy (CP); Other move-related impairments (LA, les autres); Spinal cord injury (SCI); Visually impaired (VI)

Prior to the introduction of the freestyle technique at the PWG in Innsbruck in 1984, female and male Para skiers used the classical skiing technique for all distances, but the first official use of the freestyle technique was in a medal race in Tignes Albertville, France, in 1992. Since then, events have been split into races of various distances by skiing style (i.e., the classical or freestyle skiing technique) (Figure 1).[4]

Before skiers could participate in PWG they were subject to a classification process, whereby skiers with similar observable characteristics related to their disabilities were grouped together for competition purposes.[5] In 1992 a fundamental change in the classification process was introduced, with a move away from a strategy based on the skiers' medical diagnosis towards a more functional sport-related approach. Thereafter, the classification was based on the functional impact of the skiers' disability on their sport-specific performance (Figure 1).[5, 6] Today, the functional sport-related approach is still used to classify Para skiers for competition.

1.2 CLASSIFICATION AND TIME FACTORS IN PARA CROSS-COUNTRY SKIING

In Para cross-country skiing, the classification system is used to ensure fair competition between the skiers with different disabilities and to minimize the impact of their disabilities on the outcome of competitions. Accordingly, female and male Para skiers are divided into three different categories: (1) physically impaired sitting skiers, (2) physically impaired standing skiers, and (3) visually impaired standing (VI) skiers. Within these three categories, Para skiers are further divided into several classes, based on the functional impact of their disability on their performance: LW10-12 for sitting, LW2-9 for standing, and B1-3 for VI (Table 1).[7] Due to few skiers in each class, competitions are carried out across classes within each category, using a class-specific time factor.[2, 7, 8] After a race, the skier's actual time is multiplied by the time factor to calculate the adjusted race time and overall ranking.[2, 7] The time factor is larger for skiers with disabilities that affect their performance less, such that skiers with the most severe disabilities receive the maximum time bonus.[9]

Table 1. Overview of the Para cross-country skiing categories, classes (higher (red); middle (yellow); lower (green))[(I)], impairment type, skiing posture and equipment, and time factor for the classical and freestyle skiing technique.[2, 7, 10]

Category	**Class**	**Impairment**		**Skiing posture and equipment**	**Time factor (%)**	
					Freestyle	Classical
Physically impaired sitting	**LW10**	Legs and trunk	Impairments in both legs and unable to sit without arm support	Primarily with high knees, "knee-high" (Figure 2) A sledge mounted on two skis, plus two poles	-	86
	LW10.5		Impairments in both legs but can keep balance if not moving sideways	Primarily "knee-high" A sledge mounted on two skis, plus two poles	-	88
	LW11	Legs	Impairments in both legs but can keep balance when moving sideways	Either "knee-high" or with the knees low "kneeing" (Figure 2) A sledge mounted on two skis, plus two poles	-	93
	LW11.5		Impairments in both legs but nearly normal trunk control	Primarily "kneeing" A sledge mounted on two skis, plus two poles	-	95
	LW12		Similar leg impairments as LW2-4 skiers Normal trunk control but have chosen to compete sitting	Primarily "kneeing" A sledge mounted on two skis, plus two poles	-	100
Physically impaired standing	**LW2**	Leg(s)	Impairment in one leg, e.g., amputation above knee	Skiing with prosthesis, two skis, and two poles	93	92
	LW3		Impairments in two legs, e.g., muscle weakness	Skiing with two skis and two poles	87	86

	LW4		Impairment in one leg, e.g., amputations above the ankle or reduced muscle control in the lower part of the leg	Skiing with two skis and two poles	96	97
	LW5/7	Arm(s)	Impairment in both arms, e.g., no hands or reduced grip force	Skiing with two skis, but without poles	89	79
	LW6		Impairment in one arm, e.g., amputation above elbow	Skiing with two skis and one pole	95	90
	LW8		Impairment in one arm, e.g., no elbow or finger flexion or amputation below elbow	Skiing with two skis and one pole	96	92
	LW9	Arm(s) and leg(s)	Impairments in arm(s) and leg(s), e.g., reduced coordination in all extremities or amputation in one arm and one leg	Skiing with two skis and one or two ski poles	88	87
Visually impaired standing	B1	Vision	Blind or very low visual acuity. No light perception	Must wear blackout glasses Skiing with a guide	88	88
	B2		Higher visual acuity than B1 skiers. Small visual field (< 10° diameter)	May ski with a guide.	99	99
	B3		Reduced visual acuity and/or visual field (< 40° diameter)	May ski with a guide	100	100

[I] The division into the higher, middle, and lower classes is not recognized by the IPC as a standardized division, but it was used for simplification purposes.

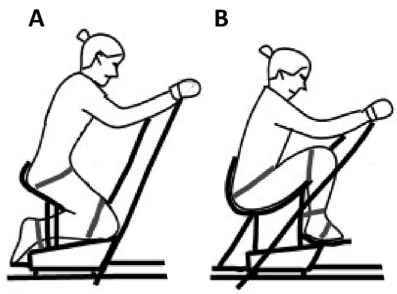


Figure 2. The most frequently used sitting positions in sit-skiing, with the knees low “kneeing” (A) and with the knees in a high position “knee-high” (B).

1.3 THE DEMANDS OF PARA CROSS-COUNTRY SKIING

Competitions for elite Para skiers and able-bodied skiers comprise races during several World Cups events every season, one World Championship every second year, and one Paralympic Winter Games (PWG)/Olympic Winter Games (OWG) every fourth year.[11] While standing, VI, and able-bodied skiers compete in races using either the classical skiing technique or the freestyle skiing technique, sitting skiers only compete in races using the classical skiing technique.[10, 11] The competitions take place in snow-covered racecourses, with distances ranging from 0.8 km to 20 km for Para skiers, and 1.2 km to 50 km for able-bodied skiers. Furthermore, the racecourses consist of undulating terrain, changing between uphill, flat, and downhill sections, with inclines ranging from -14% to 16% for sitting skiers,[10] -18% to 18% for standing and VI skiers,[10] and -20% to 20% for able-bodied skiers.[12] Approximately 50% of the time is spent in uphill terrain, which is also where the largest performance differences seem to occur.[13-18] Additionally, substantial variations in external conditions (e.g., temperature, wind, snow conditions, height over sea level) may occur between or during races. Together, the terrain and external conditions during races will lead to substantial variations in skiers’ speed, which is regulated by their choice of pacing strategies, sub-techniques, and related kinematic patterns.[19-23] The choice of sub-technique and regulation of kinematic patterns are complex and are influenced by individual preferences, and internal and external factors (Figure 3).[22, 24-29]

1.3.1 SKIING STYLES AND SUB-TECHNIQUES

Cross-country skiing competitions are held with two main skiing techniques: classical and freestyle. For each skiing technique, skiers can alternate between five to six sub-techniques, which act as a gearing system according to the changing terrain and skier’s speeds (Table 2). With the classical skiing technique, skiers alternate mainly between double poling (DP), which is used at higher speeds on a wide range of inclines,[30, 31] double poling with kick (DK), which is used at moderate speeds in the transition between different terrains,[32] and diagonal stride (DIA), which is primarily used at low speeds in moderate to steep uphill terrain (Table 2).[25, 29]

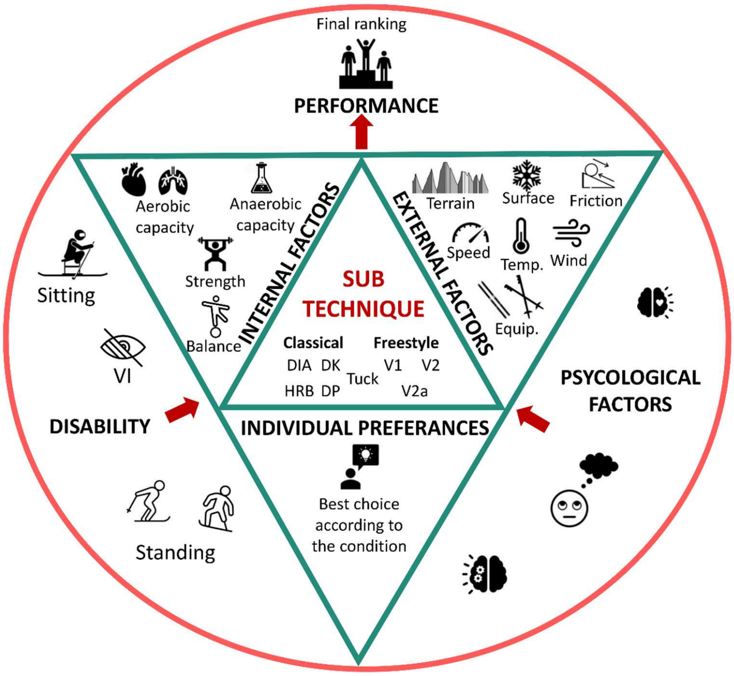


Figure 3. Factors that may affect the choice of sub-techniques in a complex interaction.
Diagonal stride (DIA); Double dance (V2); Double poling (DP); Double poling with kick (DK); Equipment (Equip.); Padling (V1); Physically impaired sitting skiers (Sitting); Physically impaired standing skiers (Standing); Single dance (V2a); Snow condition (Surface (e.g., hard, loose, wet) and Friction (between ski and snow)); Temperature (Temp.); Tuck position (Tuck); Visually impaired standing skiers (VI)

In the freestyle skiing technique, skiers alternate mostly between V2a, which is primarily used in flat and slightly uphill terrain, V2, which is normally used in slightly to moderate steep uphill, and V1, which is primarily used in step uphill (Table 2).[21, 33] In both skiing techniques, skiers employ a tuck position without pole- and leg actions during downhill sections, and various turn techniques are adapted to manage turning.[19, 34] Furthermore, for each of the sub-techniques, the speed is adjusted through the kinematic patterns and requires upper and/or lower body work to different extents.[21, 35, 36] It has been suggested that in able-bodied cross-country skiing there are speed[22, 27, 28] and incline[25, 26, 29] thresholds for the use of the sub-techniques. Also, the skier's physical capacity will affect the selection of speed and sub-technique[36, 37] and especially in uphill terrain, both performance and level of strength have been linked to more frequent selection of higher gears (i.e., DP, DK, and V2 compared with DIA and V1, respectively).[38] In this context, the ability to use the different sub-techniques may additionally be dependent on functional limitations related to the individual disability among standing and VI skiers. Accordingly, Para skiers with a standing posture and able-bodied skiers may select different sub-techniques at similar speeds.

Table 2. Overview of the sub-techniques used within the classical and freestyle skiing technique.

Skiing technique	Sub-technique	Gear	Incline[I] (%)	Speed[II] ($m \cdot s^{-1}$)	Movement	
Classical	Upper-body double poling	1	-14 - 16		Symmetrical arm poling, while sitting[III] in a sledge mounted on two skis.	
Classical	Herringbone (HRB)	1	> 12.0	< 3.0	Diagonal arm and leg movement, without ski gliding. Ski angled.	
	Diagonal stride (DIA)	2	5.0 - 14.0	1.5 - 4.0	Diagonal and parallel arm and leg movement before leg kick.	
	Double poling with kick (DK)	3	3.5 - 11.5	3.0 - 7.5	Symmetrical arm poling, while ski gliding followed by one leg kick.	
	Double poling (DP)	4	-3.5 - 10.5	4.0 - 9.5	Symmetrical arm poling, while ski gliding without leg kick.	
	Tuck position	5	< -3.5	> 9.0	Tucked position without pole and leg actions.	
Freestyle	Diagonal skate	1	> 12.0	< 3.0	Diagonal arm and leg movement with ski gliding.	
	V1	2	9.0 - 13.0	1.0 - 4.0	Asymmetrical double poling during every two leg actions.	
	V2	3	0.0 - 10.5	2.5 - 9.5	Symmetrical double poling for every leg action.	
	V2a	4	-3.5 - 1.0	6.5 - 10.0	Symmetrical double poling for every two leg actions.	
	Skating without poles	5	-10.5 - -2.0	9.0 - 11.0	Leg actions without poling.	
	Tuck position	6	> -9.0	> 10.0	Tucked position without pole and leg actions.	

(I) Presentation of inclines at which the sub-techniques are primarily used.
(II) Presentation of speed at which the sub-techniques are primarily used.
(III) Different sitting positions for the disability classes, see Table 1 and Figure 2.

1.3.2 KINEMATICS

The kinematic pattern (e.g., cycle length (CL), cycle rate (CR), cycle time (CT), poling time (PT), and swing time (ST)) is used to adjust skiing speed, but is regulated differently according to sub-technique, terrain, and initial speed,[31, 32, 35, 39-43] as well as to the skier's own limits of individual physical and technical capacities (Table 3 and Appendix 1).[41, 42, 44-46] CL is the distance covered between two consecutive starts of pole-ground contact by the same pole. CR is the number of cycles per second. CT is the duration of a full cycle, in which PT is the period of pole-ground contact during the poling phase, and ST is the period without any pole-ground contact during the recovery phase. A skiers' ability to produce power rapidly through a high CR is important for accelerating at the beginning of races, attacking in steep uphill terrain, and sprinting towards the finishing line.[47] In both sit-skiing[13] and able-bodied cross-country skiing,[22, 48-52] CR increases with higher speeds, regardless of sub-technique and terrain (Table 3). Nevertheless, regardless of sub-technique and terrain, CL is the main determinant of able-bodied skiers' performance.[38] Consistently, able-bodied skiers increase CL when their speed become faster on a constant incline,[22, 53] and either reaches a plateau[49, 51] or decreases[48, 50] at maximal speed depending on sub-technique and incline (Appendix 1). Sitting skiers' CL in uphill terrain only increases when their speed increases (Table 3). However, the effect at maximal speed has not yet been investigated. Compared with flat or less inclined terrain, when skiing in uphill terrain, sitting and able-bodied skiers utilize shorter CL,[14, 23, 31, 43, 53] together with relatively longer PT (% of full cycle time) (Table 3 and Appendix 1).[14, 31, 35, 43] In able-bodied cross-country skiing, the relatively longer PT is associated with a lower speed in uphill terrain compared with in flat terrain, which allows a higher production of work per cycle ($work_{cycle}$) and thereby a higher work rate (WR).[31] However, when able-bodied skiers were DP at identical WR, it has been found a higher CR and lower $work_{cycle}$ in uphill terrain compared with in flat terrain (Appendix 1).[31, 35] By contrast, sitting skiers have displayed similar CR across different types of terrain (Table 3),[13] but WR, $work_{cycle}$, and other cycle characteristics have not yet been investigated for sitting skiers. Knowledge of these factors would increase our understanding of the demands of skiing on different terrains and how skiers with different impairments utilize the kinematic patterns to adjust their skiing speed.

1.3.3 KINETICS

In most sub-techniques, the standing skiers uses their upper and lower body to generate propulsive forces that are applied to the ground through the poles and skis to achieve forward motion, whereas the sitting skiers apply the propulsive forces through the poles by using only their upper body. The transformation of the generated forces to speed is dependent on a coordinated interaction between the joints and segments of the upper and/or lower body (e.g.,[30, 41, 54]). In each sub-technique the propulsive phases are distributed differently between skis and poles during a cycle,[25, 29-31, 55, 56] and the time coordination and proper moment of force application seem to be factors that distinguish between faster and slower skiers.[57] Compared with slower skiers, faster skiers reach higher peak forces later in the poling phase and attain longer CL, characterized by a longer recovery phase, when using the DP, DIA, and

Table 3. Overview of the effect of the kinematic patterns of different conditions during sit-skiing.

CONDITION	PARAMETER	EFFECT	TERRAIN Flat	TERRAIN Downhill	TERRAIN Uphill	RESEARCH
Increasing intensity	**CL**	→	X	X		13
		↑			X	
	CR	↑	X	X	X	
Uphill compared with flat	**CL**	↓				14
	Duty cycle	↑				
Higher-level compared with lower-level performance	**CL**	↑	X		X	14
	Duty cycle	↑	X			
		↓			X	
Increasing impairment level	**CL**	↑	X			58
	CR	↓	X			
	PT_{rel}	↓	X			
	ST_{rel}	↑	X			
	V_{max}	↑	X			
Correlations	**CL and cycle speed**	✚	X		X	14
	CL_{submax} and V_{max}	✚	X			58

Cycle length (CL); Cycle length at submaximal speed (CL_{submax}); Cycle rate (CR); Double poling (DP); Maximal velocity (V_{max}); Percentage ratio between PT and CT (Duty cycle); Relative poling time (PT_{rel}); Relative swing time (ST_{rel}); No change (→); Increase (↑); Decrease (↓); Positive correlation (✚)

V2 sub-techniques.[30, 57] Additionally, for DIA, a higher force impulse during a shorter leg push-off, followed by a longer leg swing and gliding phase has been related to better performance.[54] In a study of sit-skiing, it was found that a greater range of motion during trunk flexion, lower CR, and smaller pole angles to the ground were utilized by skiers who achieved the highest levels of force production compared with skiers with lower force production.[58] Additionally, the highest levels of force production were achieved by sit-skiers in the higher and middle classes (i.e., LW11.5–LW12), while sit-skiers in the lower classes (i.e., LW10–10.5) had the lowest levels of force production.[58] In a separate study it was found that the difference in force production between classes was probably attributed the complex role of the trunk (e.g., momentum, position, and stability) during sit-skiing.[58] However, the study was limited to two speeds performed over a short distance in flat terrain. Therefore, more research is needed on the properties of force production in different terrain and at a wider range of skiing speeds for both sitting, standing, and VI skiers.

1.3.4 ENERGETICS

During cross-country skiing races, substantial variations in speed challenge the skier's ability to distribute their work and energy expenditure throughout the race, which is termed pacing strategy.[59] A positive pacing strategy (i.e., when speed is reduced during the race) between laps is often applied in sprint and distance races.[17, 19, 23, 60-62] Additionally, large variations in WR and metabolic demands occur within laps due to changing terrain. In able-bodied cross-country skiing, WRs corresponding to ~120–160% of peak oxygen uptake ($\dot{V}O_{2peak}$) have been observed in the uphill sections during both sprint (≤ 1.8 km)[18, 63, 64] and distance (≥ 10 km)[17] performances. It has been found that in cases of the high WRs in uphill terrain, skiers increased their anaerobic turnover and repeatedly had oxygen deficits of 0–50% of the maximal accumulated oxygen deficit during a simulated roller-skiing distance race.[65] Since skiers' anaerobic capacity is limited, they are dependent on recovery to avoid involuntary reduction in WR, and hence reduction in performance. It has been found that during downhill sections, oxygen demand drops to ~40–65% of $\dot{V}O_{2peak}$,[47, 66] which seems sufficient to reach a state of recovery to sustain the repeated supramaximal WRs during uphill sections.[17, 21] Due to the standing skiing position, it is likely that the energetics across the race course for standing and VI skiers would be relatively similar to that for able-bodied skiers. To date, only one case study of a sit-skier has estimated WR during sit-skiing,[13] and the researchers found that a higher absolute WR was reached in uphill terrain compared with in flat terrain during a high-intensity training session.[13] Still, the question of how the physiological and biomechanical performance-determining factors are influenced by different types of terrain in sit-skiing and their relation to the production of WRs remains to be investigated.

1.4 PERFORMANCE-DIFFERENCES IN PARA CROSS-COUNTRY SKIING

Able-bodied cross-country skiing has generally been the most investigated individual winter sport[47] and the focus on evidence-based practice has increased in recent years.[67] An improved understanding of performance demands and associated differences in race times is useful both for skiers with a disability (Para) and skiers without a disability (able-bodied).[68, 69] Hence, knowledge of how race times differ from the winner to other rankings provides insight for skiers and their coaches during the goal setting process and monitoring of training progress. To date, research on differences in race time have only been conducted in able-bodied cross-country skiing, with the differences in race time between the top 10 competitors being slightly larger in female able-bodied skiers (~0.8%) compared with male able-bodied skiers (~0.1%).[70] However, it is not known whether differences in race times differ between Para and able-bodied skiers, or to what extent the time factor affects differences in race times across the Para cross-country skiing categories (i.e., sitting, standing, and VI). Since the purpose of the time factor is to ensure fairness by reducing disability-related differences between skiers during competitions, it is reasonable to assume that differences in race times would be smaller for adjusted race times than for unadjusted ones. Thus far, there have not been any studies of whether the differences in race times for both adjusted and unadjusted race times are related to the distribution of classes within the Para cross-country skiing categories.

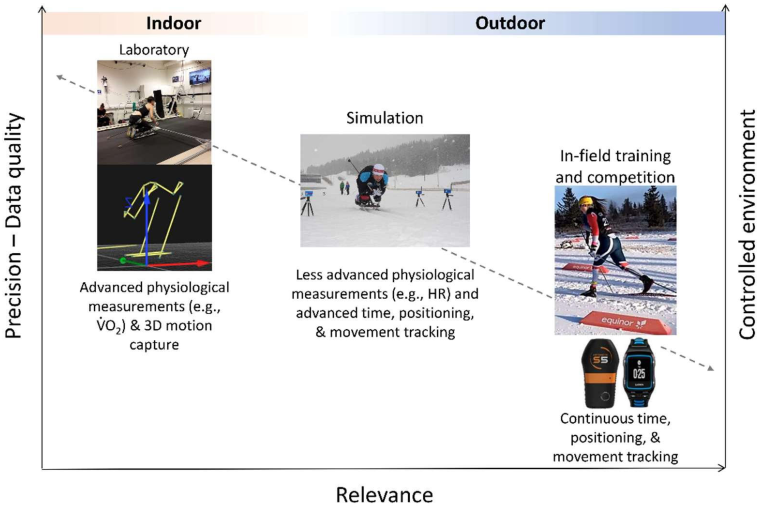


Figure 4. Graphic representation of how indoor testing and outdoor testing within different environments influence the precision, quality, and relevance of the collected data.

In applied sports science, one of the main goals is to collect data directly during competitions. During a real-life competition nothing is controlled by the research setup, and any data collected would have high relevance for increasing our knowledge of sport-specific performance. Still, data collections during competitions can be challenging due to technological difficulties (e.g., precision and data quality), athlete participation, and logistical/administrative factors, as well as the investigation of physiological responses. Therefore, under more controlled settings, the indoor lab has been shown to be highly relevant for evaluating physiological and biomechanical responses with high precision and data quality,[18, 71] whereas the outdoor lab where a real-life setting can be simulated under controlled conditions increases the functionality of the outcome (Figure 4). Therefore, the research settings in the laboratory ("indoor lab")[29-31, 35, 42, 43, 72-75] and simulated in-field competitions ("outdoor lab")[17, 18, 22, 62, 76-78] have frequently been used in studies of able-bodied cross-country skiing, and they can be of high value in Para cross-country skiing.

In cross-country skiing races, skiers cover a pre-defined distance along a track in the shortest time possible. During a race, intermediate times are commonly used to describe the development of a race for skiers, coaches, and spectators. Such information provides insights into the skiers' performance and the development of the race, although the information is limited from a scientific perspective. As changes in a skier's race performance happen more frequently than the time elapsed at the checkpoints along the track, tracking skiers' positions continuously from start to finish would provide detailed information on the development of their performance in the race (Figure 5).

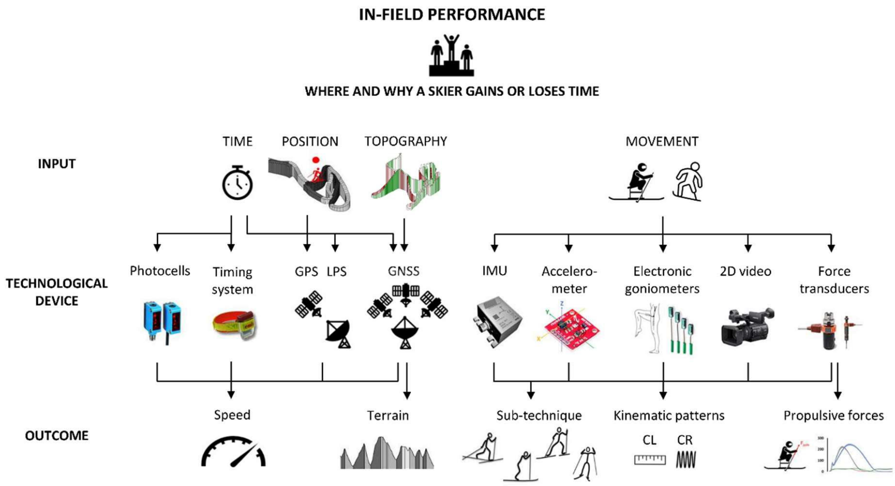


Figure 5. Overview of technological devices that can be employed to measure performance-related factors and other factors affecting performance (outcome) for analysis of in-field cross-country skiing performance. Cycle length (CL); Cycle rate (CR); Inertial measurement unit (IMU); Global navigation satellite systems (GNSS) Global positioning system (GPS); Local positioning system (LPS)

1.4.1 POSITION-TIME TRACKING

The primary technologies used to track athletes' position and time continuously are video-based tracking, local positioning systems (LPS), and global navigation satellite systems (GNSS) (Figure 5 and Appendix 2).[79, 80] Video-based tracking is only usable for limited distances[18, 45, 81] or in the field of view of a camcorder throughout the race.[19] Additionally, data storage during collection is limited, and the method is time-intensive and requires a relatively lot of data processing before it can be useful for skiers and coaches. Therefore, the use of video-based tracking in outdoor endurance sports (e.g., cross-country skiing) is limited. LPS measure the range between mobile nodes carried by the athlete and a number of stationary infrastructure nodes with a known location.[82] The installation of the locators around the racecourse can be time-consuming in cases of frequent use of LPS,[80] which probably has limited its use in cross-country skiing. Today, GNSS devices are the most commonly applied wearable technological systems to track endurance athletes' performance in outdoor sports.[83] The types of GNSS receivers used include single-frequency chips in smartphones and wrist-worn training watches (e.g., Garmin Forerunner 305 and 920XT), standalone units (e.g., Catapult OptimEye), and high-end differential geodetic receivers (e.g., ZXY-Go system, Leica RTK), which normally are carried on the athlete's back during training and competition.[83, 84]

Within these different types of GNSS receivers, the hardware and software quality and complexity differ substantially, which in turn affects measurement accuracy.[79, 84] Compared with low-cost GNSS receivers (e.g., smartphones and wrist-worn training watches), both standalone units and high-end differential receivers have been found to have greater accuracy for analyses of vertical positions, horizontal plane positions, speed, acceleration/deceleration, and time.[83, 84] Gløersen et al. 2018[83] state that the ZXY-Go and Catapult OptimEye receivers are suitable to detect speed differences in cross-country skiing instantaneously, whereas the Garmin watch receiver is not able do this, due to the receiver's horizontal plane speed errors (ZXY-Go: IQR [0.036,0.043], Catapult: IQR [0.070, 0.075], and Garmin-920XT: IQR [0.614, 0.835] $m \cdot s^{-1}$). An overview of previous studies that have assessed the accuracy of position, displacement, speed, and acceleration using different GNSS methods is provided in Appendix 2.

1.4.2 MOVEMENT TRACKING

Elite skiers are mainly dependent on achieving the highest average skiing speed over a given distance in order to win a medal. Attaining a high average speed across a racecourse is, among other factors, influenced by the sub-techniques used and related kinematic patterns.[19-23] Therefore, detection and analysis of the used sub-techniques and kinematic pattern are important for improving athletic performance as they provide information on why skiers gain or lose time compared with their competitors (Figure 5). For technological devices to be effective measuring tools, the devices and related data analyses need to be accurate, reliable, and time-efficient.[85] Several devices have been used for analyzing sub-technique and kinematic patterns, including video-based systems,[18, 19, 45, 81] electronic goniometers,[30, 86, 87] accelerometers,[88] specially designed pole and ski force transducers (e.g.,[87, 89-93]), and inertial measurement units (IMUs) (e.g.,[78, 85, 94-101]) (Appendix 2). Even though a video-based system is a low-cost method that is easy to use, it has a limited capture volume, involves time-consuming data processing, and is sensitive with regard to the depth of field, which requires the camera to be perpendicular in plane to the skier to reduce positioning errors.[102] By contrast, electronic goniometers have unlimited capture volume but are unsuitable for measuring angles in the shoulder joint which is involved in the execution of both the classical and freestyle sub-techniques. Accelerometers that measure acceleration are useful tools to measure movement change, but analysis of acceleration in all three planes, especially in the horizontal direction, is limited if only one accelerometer is used.[100] Pole and ski forces measured from instrumented poles and force plates beneath the snow can be used to identify ground-contact kinematic patterns (e.g.,[87, 89-92, 103]). Although instrumented poles and skis are used during in-field skiing, it is often necessary to modify the skier's equipment,[89, 103] which in turn may affect the skier's technique and possible performance. IMUs are small, wireless sensors that are sensitive to motion and have the potential to collect data with high frequency in any field activity (e.g., throughout a skiing race).[104, 105] An IMU is a sensor that combines an accelerometer and a gyroscope, in some instances also combined with a magnetometer, that measure linear acceleration, angular rate, and/or magnetic field strength, from which speed and displacement can be calculated by using time integration.[102] However, IMUs have some risks with regard to the external validity of the measurements, with accelerometers that are sensitive to gravity and gyroscopes that are sensitive to drifting errors. Furthermore, IMUs measure within a local coordinate system, and consequently the initial position, speed, and orientation are unknown in a global coordinate system, although inputs from other sensors (e.g., GNSS) can strengthen external validity.[102] IMUs have become an effective tool for measuring movement data in order to assess sub-technique and kinematic performance in cross-country skiing.[78, 85, 96-101, 106, 107] Some of the most recent studies of in-field able-bodied cross-country skiing have shown an automatic classification of the sub-techniques with an accuracy of 90–100% with the use of IMUs in combination with GNSS and machine learning algorithms (Appendix 2).[78, 95, 96, 99, 101] Thus, the use of wearable devices such as GNSS to track position, time, and acceleration, in combination with IMUs to measure the orientation of the body, has been revolutionary for advanced in-field performance analysis in able-bodied cross-country skiing.[22, 24, 27, 28, 36, 78, 85, 94] By contrast, research on position, time, speed, sub-technique use, and related kinematic patterns in Para cross-country skiing has been limited.[13, 14, 58, 108-113] To date, speed has only been investigated in sit-skiing by using a radar system,[58, 111] Emit EQ Timing system,[110] and a GNSS system (i.e., Garmin Forerunner 920XT).[13] Furthermore, investigations of kinematic patterns have been done using 2D video-based tracking,[14, 108, 109, 113] instrumented skiing poles with force transducers,[111] and IMU.[13] The investigations of speed and kinematic patterns were limited to specific sections during a race,[14, 108, 109] simulated skiing in a ski tunnel,[58, 111, 113] split time analyses,[110] and a case study (Appendix 2).[13] Therefore, a framework for advanced in-field performance analyses, in which GNSS technology and micro-sensor units (e.g., IMU) are combined, would provide new insights into the technical aspects (e.g., sub-technique selection and related kinematic pattern) and tactical aspects (e.g., speed and pacing) of Para cross-country skiing performance (Figure 5).

1.5 PHYSIOLOGICAL PERFORMANCE-DETERMINING FACTORS

The performance-determining factors in Para cross-country skiing, including maximal oxygen uptake ($\dot{V}O_{2max}$), the fractional utilization of $\dot{V}O_{2max}$, performance oxygen (O_2) deficit, and efficiency[42, 114, 115] are probably the same as those in other endurance sports. The $\dot{V}O_2$ maintained during an endurance competition, known as performance $\dot{V}O_2$,[114] is the product of $\dot{V}O_{2max}$ and the percentage of $\dot{V}O_{2max}$ at the lactate threshold (LT), and their interaction determines how long a given rate of aerobic metabolism can be sustained (Figure 6). $\dot{V}O_{2max}$ is defined as the highest rate at which oxygen can be taken up and utilized by the body during exercise, which is most often reached during running. Therefore, $\dot{V}O_{2peak}$ is normally used in analyses of the different sub-techniques in cross-country skiing.[47, 116-119] It can be achieved when large muscle groups are involved and requires a high cardiac output, muscle blood flow, muscle oxygen extraction, and total body hemoglobin.[114, 120, 121] In addition, even though the relative amount of anaerobic metabolism is small in events lasting 13–30 minutes, it contributes ~10–20% of total adenosine triphosphate (ATP) turnover.[114]

Also, demands on anaerobic capacity (measured as the accumulated O_2 deficit) have been found important in able-bodied cross-country skiing, especially sprint performance.[63, 122] Furthermore, efficiency is a measure of the effectiveness of transforming metabolic energy to external power and speed.[114]

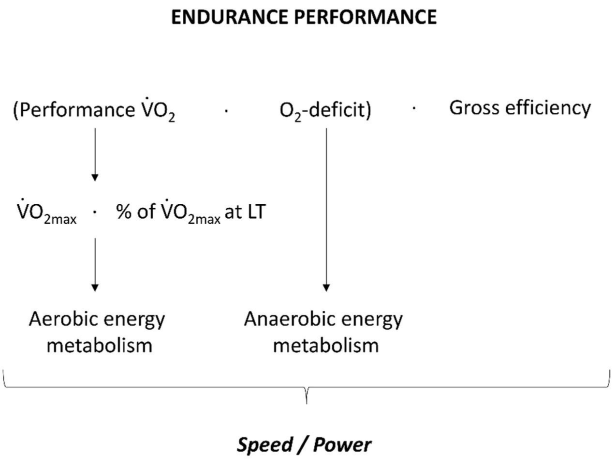


Figure 6. Overview of physiological variables that interacts during an endurance exercise performance (modified from Joyner and Coyle (2008)).[114]
Lactate threshold (LT); Maximal oxygen uptake ($\dot{V}O_{2max}$); Oxygen (O_2); Oxygen uptake ($\dot{V}O_2$)

With regard to physiological characteristics, sitting skiers have shown the highest $\dot{V}O_{2peak}$ values compared with athletes in other Paralympic sitting sports.[123-125] This finding is in accordance with findings relating to able-bodied skiers, who display some of the highest incidences of $\dot{V}O_{2max}$ compared with other endurance athletes, with values of 70–80 $mL·kg^{-1}·min^{-1}$ and 80–90 $mL·kg^{-1}·min^{-1}$ for female and male skiers, respectively.[117, 126-129] Nevertheless, able-bodied skiers reach a 6–14% higher $\dot{V}O_{2peak}$ when utilizing DIA and V2 in uphill terrain than DP in flat terrain,[117, 119, 128] but $\dot{V}O_{2peak}$ achieved when utilizing DP in both flat and uphill terrain have currently not been compared in either sitting, standing, VI, or able-bodied skiers. Furthermore, able-bodied skiers display higher gross efficiency (GE) in uphill terrain compared with in flat terrain, which explains their ability to produce higher WRs when skiing uphill.[72, 76] However, how these performance-determining factors are influenced by different terrain in sit-skiing, and their relation to WR production, remains to be investigated.

Para skiers' disabilities reduce, to some extent, their physiological functioning and/or ability to produce power. Generally, compared with skiers using a standing skiing posture (standing and VI skiers), skiers using the sitting posture (sitting skiers) reach a lower $\dot{V}O_{2peak}$, peak ventilation, and oxygen pulse,[130] which together limits their performance. For sitting skiers, the sitting positions will also have an effect on the performance-determining factors.[131-133] At present, comparisons of several physiological and biomechanical performance-determining factors between different sitting positions have only been performed in able-bodied skiers.[132, 133] In one study it was found that compared with a "knee-high" posture, skiers in the "kneeing" posture (Figure 2) used less oxygen more efficiently, and had lower ventilation, lower CR, higher force impulse, and larger range of motion in the hip,[132] which together can enhance performance. Direct generalization of the findings related to posture-dependent differences to sitting skiers may be limited, but it is obvious that the sitting position alone are disadvantageous for performance for skiers in the lower classes (i.e., "knee-high") compared with the sitting position used by the higher classes (i.e., "kneeing").

1.6 PERCEPTUAL AND PHYSIOLOGICAL PARAMETERS FOR INTENSITY REGULATION

During skiing races, skiers continuously receive feedback (e.g., perception of effort) from their body, which they can use to adjust the skiing intensity to optimize speed and finish within the shortest time possible. Also, during training, the skier must adjust the intensity according to the training stimuli that is necessary to develop skiing performance over time. In able-bodied cross-country skiing, perceptual parameters (e.g., rating of perceived exertion (RPE)) and physiological parameters (e.g., percent of HR_{max} ($\%HR_{max}$), percent of $\dot{V}O_{2max}$ ($\%\dot{V}O_{2max}$), and blood lactate concentration (BLa)) are often used to evaluate and control the intensity by employing an standardized intensity scale.[134] In a 3-zone scale, the zones are defined by physiological breakpoints of the first- and second-lactate turn points, with Zone 1 referring to low intensity below the first LT (BLa < 2 $mmol \cdot L^{-1}$), Zone 2 referring to moderate intensity between the first and second LT (BLa 2–4 $mmol \cdot L^{-1}$), and Zone 3 referring to high intensity above the second LT (BLa > 4 $mmol \cdot L^{-1}$) (Figure 7).[134, 135] Additionally, RPE is frequently assessed according to Borg's intensity scale (Figure 8),[136, 137] and a strong relationship has been established between RPE and exercise intensity.[138] Even though the standardized intensity scale is frequently used by endurance athletes (e.g., able-bodied skiers), caution is necessary, as the intensity scale does not take into account activity-specific variation (e.g., activities with less active muscle mass often produce higher BLa) and individual variation (e.g., in the HR–BLa relationship).[139, 140] In this regard, several studies have found lower HR when DP compared with other classical and freestyle sub-techniques and running, despite similar ventilation, BLa, and RPE when compared at similar speeds[141] and at the BLa threshold.[142] As sit-skiing is performed with less active muscle mass than when performing standing whole-body activities (e.g., cross-country skiing with a standing position and running), it can be speculated that the perceptual and physiological parameters would display different values within the intensity zones.[143] Furthermore, in a case study of a sit-skier, the HR and RPE during low intensity training were closer to the corresponding values during high intensity training in uphill terrain than in flat and downhill terrain.[13] Therefore, investigation of how the perceptual and physiological parameters differ during sit-skiing in different terrain might lead to the development of an important tool for sit-skiers and their coaches for planning, executing, and evaluating training, and to develop performance in competition over time.

3-zone	Intensity	%HR_{max}	%$\dot{V}O_{2max}$	BLa ($mmol \cdot L^{-1}$)	RPE (6-20)
1	Low	55-82	45-80	0.8-2.0	< 11-13
2	Moderate	83-87	81-87	2.1-4.0	14-16
3	High	88-100	88-100	4.1-10.0	17-20

Figure 7. A standardized 3-zone intensity scale described by perceptual parameters (i.e., RPE) and physiological parameters (i.e., %HR_{max}, %$\dot{V}O_{2max}$, and BLa) frequently used by able-bodied athletes. The scale is based primarily on decades of testing of able-bodied skiers, biathletes, and rowers.[134, 135] Blood lactate concentration (BLa); Percent of maximal oxygen uptake (%$\dot{V}O_{2max}$); Percent of maximal heart rate (%HR_{max}); Rating of perceived exertion (RPE)

6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	Maximal exertion

Figure 8. The rating of perceived exertion (RPE) according to Borg's 15-grade intensity scale [modified in accordance with Borg, 1982].[137]

1.7 THE RATIONALE FOR THIS THESIS

While able-bodied cross-country skiing is the most investigated individual winter sport,[47] the scientific understanding of Para cross-country skiing performance is sparse. Overall, Para and able-bodied cross-country skiing (e.g., performance-determinants, competitions events, race distances, skiing techniques, racecourses, external conditions, and equipment) are similar in nature, but the different impairments of Para skiers clearly influence cross-country skiing performance. Therefore, increased understanding of the specific demands of Para cross-country skiing would be of high value for the sport.

During a Para cross-country skiing race, the time differences that occur between skiers indicate the improvement in performance needed to gain a better rank or win the race. Even though a skier's rank is determined by their final race time, detection of continuous data (e.g., time, position, and movement) during a race will provide information on where and why a skier is gaining or losing time compared with their competitors. With this in mind, using wearable devices (e.g., GNSS and IMU) to track skiers' in-field performance continuously has been revolutionary in able-bodied cross-country skiing,[22, 24, 27, 28, 36, 78, 85, 94] but similar advanced in-field performance analysis in Para cross-country skiing have so far been limited.[13, 14, 58, 108-113] Therefore, the evaluation of a framework for advanced in-field performance analyses would help to provide new insights into the technical and tactical aspects of Para skiers' performance across differing types of terrain during an entire race. Additionally, such a framework might be used to increase our understanding of the differences in skiing performance between Para cross-country skiing categories and competition classes, as well as between sexes. Furthermore, details of the physiological and biomechanical performance-determining factors, which may explain why a skier gains or loses time across different terrains, would be of high value. Such information, together with the knowledge of differences in race times, could be used by skiers and their coaches when new goals are defined and training progress evaluated for development of the skiers' performance. Physiological and biomechanical performance-determining factors, the testing approach used investigating these in the laboratory, and incorporation of the results into training (e.g., intensity regulation) are well established in able-bodied cross-country skiing.[31, 36, 42, 63, 72, 128, 144-146] However, details of the performance-determining factors across different terrains and how to investigate those factors, as well as the incorporation of the results into training are lacking in Para cross-country skiing, especially for sitting skiers, who have a different skiing posture than standing, VI, and able-bodied skiers.

2 AIMS

The overall aim of the research for this thesis was to investigate differences in race times and performance-determining factors in Para cross-country skiing. This was done through three interconnected studies that combined several testing methodologies, to (1) provide an overview of cross-country skiing performance across Para categories (analyses of race times in historical competition data), (2) evaluate the feasibility of a framework for investigation of in-field Para cross-country skiing performance (case series comparing time, speed, and movement data between Para and able-bodied skiers), and (3) investigate specific physiological and biomechanical performance-determining factors when cross-country sit-skiing in different terrains (indoor lab) (Figure 9).

The specific aims of the three studies were as follows:

Study I compared differences in race time (RT_{diffs}) between female and male Para and able-bodied skiers. To investigate the effects of the time factor on RT_{diffs} for the Para skiers, analyses were performed with both adjusted and unadjusted race times. Furthermore, the study examined how RT_{diffs} changed across the 2011–2020 seasons.

Additionally, for the thesis, the distribution of classes was compared between the adjusted and unadjusted race times within the top 3 and top 8 skiers in each female and male Para cross-country skiing category.

Study II evaluated the feasibility of a framework based on micro-sensor technology for detailed analyses of in-field performance and sub-technique selection in Para cross-country skiing. This was done by using the framework in a case series to compare descriptively performance-related parameters between elite Para skiers and able-bodied skiers during a classical skiing race.

Additionally, for the thesis, a descriptive comparison of performance-related parameters between a female sitting skier, female standing skier, and female able-bodied skiers, all of elite level, was made during two parts of a classical skiing race.

Study III compared peak work rate (WR_{peak}) and associated physiological and biomechanical performance-determining factors between skiing in flat terrain and skiing in uphill terrain using upper-body double poling when cross-country sit-skiing.

Additionally, for this thesis, the perceptual and physiological parameters for intensity regulation were compared between sit-skiing in flat terrain and sit-skiing in uphill terrain at low, moderate, and high intensities.

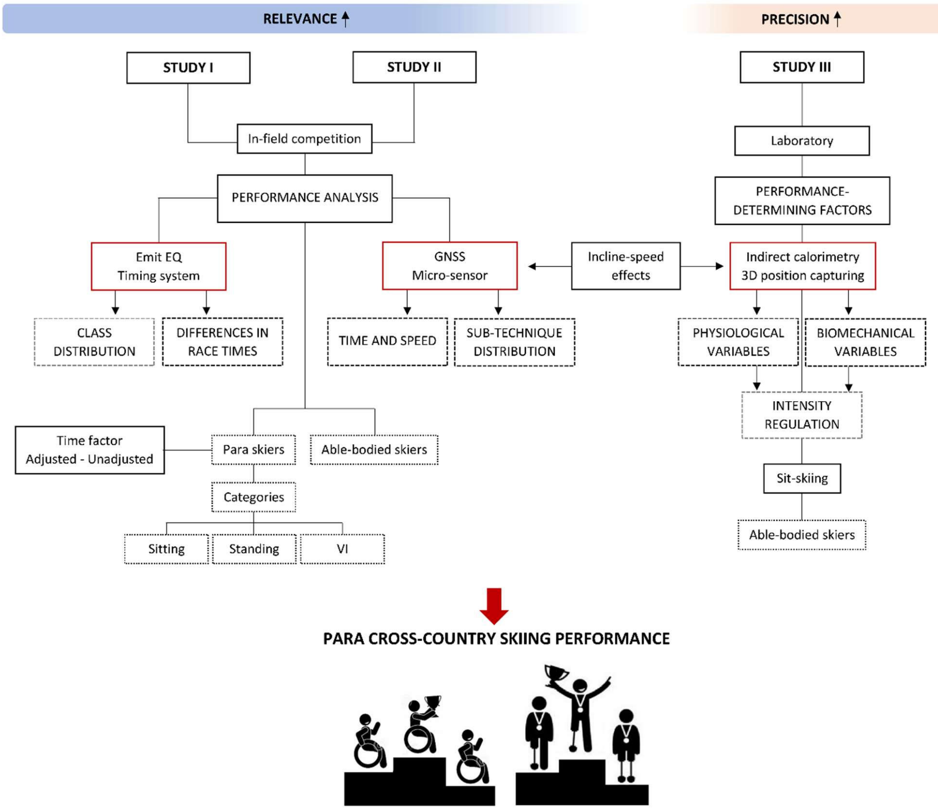


Figure 9. Overview of the three studies included in this thesis. Used methods (red boxes); analyzed outcome (black (Study I, II, and III) and gray (supplementary analyses) dashed boxes); skiers included in the studies (dotted boxes).

Global navigation satellite systems (GNSS); Physically impaired sitting skiers (Sitting); Physically impaired standing skiers (Standing); Visually impaired standing skiers (VI).

3 METHODS

Provided here is a summary of the methods used in the original articles, which the reader is referred to for a more detailed description.

3.1 OVERALL DESIGN

To get an overview of differences in race time (RT_{diffs}) of female and male Para and able-bodied skiers in the 2011–2020 seasons, analyses of historical race data were performed in Study I. Race data for Para skiers (i.e., sitting, standing, and VI) and able-bodied skiers during all World Cups, World Championships, and PWG/OWGs were obtained from the websites of the International Paralympic Committee (IPC)[147] and the International Ski Federation (FIS).[148] For each race, RT_{diffs} were calculated for both the top 3 skiers and the top 8 skiers for all skiing groups (VI, standing, sitting, and able-bodied skiers). The top 8 skiers were chosen because skiers with lower performance levels may lead to excessively larger differences in race times across the competition field compared with among the medalists, due to a disproportionate effect on RT_{diffs}. Supplementary analyses were done to investigate whether the differences in race times were related to the distribution of classes within the categories. Therefore, a comparison of the distribution of classes was performed for the female and male top 3 and top 8 skiers in each Para cross-country skiing category. Even though a skier's rank is determined by their final race time, detection of continuous time, position, and movement data during a race will provide information on where and why a skier gains or loses time compared with their competitors. Therefore, in Study II, the feasibility of employing a framework based on micro-sensor technology for in-field analyses of performance and sub-technique selection in Para cross-country skiing was evaluated. For that purpose, performance-related parameters in case series were compared between a female standing skier, two male VI skiers, and female and male able-bodied skiers, all on elite level (Study II), and between a female sitting skier, a female standing skiers, and female able-bodied skiers, all on elite level (supplementary analyses) during a cross-country skiing race on snow. Furthermore, physiological and biomechanical performance-determining factors affect performance outcome during a race, but investigation of these factors outdoor is challenging. Therefore, in Study III the performance-determining factors were investigated for upper-body double poling in flat and uphill sit-skiing on a treadmill. For this purpose, two test sessions of upper-body double poling in sit-skiing on a treadmill were completed (Study III).

3.2 PARTICIPANTS

In Study I, historical race data relating to the top 8 ranking in 131 Para cross-country skiing races and the top 8 ranking in 104 able-bodied skiing races were analyzed (Table 4). In Study II, the participants comprised one female and two male elite Para skiers from the Norwegian national team and seven elite able-bodied skiers (Table 5), while in Study III the participants comprised fifteen national-level male able-bodied skiers (Table 6). The female Para skier in Study II was a physically impaired standing LW4 skier, who had linear scleroderma with reduced leg length, joint mobility, muscle mass, and strength in one leg. The two male Para skiers in Study II were visually impaired B3 skiers (i.e., they had ~10% vision and could recognize contours at a distance of 2–6 m) and each of them was accompanied by a personal guide during the race. The supplementary analyses were performed for a female LW11 sit-skier, who had a spinal cord injury (Table 5).

Table 4. Number of races included in the analyses for Para (Sitting: physically impaired sitting skiers, Standing: physically impaired standing skiers, and VI: visually impaired standing skiers) and able-bodied skiers in Study I, divided by sex, skiing technique, and distance.

Skiers		Races (No.)	Sex	Races (No.)	Skiing technique	Races (No.)	Distance	Length (km)	Races (No.)
Para	**Sitting**	61	M	37	Classical	37	Short	5	8
							Middle	10	29
			F	24	Classical	24	Short	5	5
							Middle	7.5	19
	Standing	46	M	25	Classical	17	Short	7.5	4
							Middle	12.5	13
					Freestyle	8	Short	7.5	2
							Middle	12.5	6
			F	21	Classical	10	Short	5	2
							Middle	10	8
					Freestyle	11	Short	5	3
							Middle	10	8
	VI	24	M	18	Classical	9	Short	7.5	2
							Middle	12.5	7
					Freestyle	9	Short	7.5	1
							Middle	12.5	8
			F	6	Classical	4	Short	5	2
							Middle	10	2
					Freestyle	2	Short	5	-
							Middle	10	2
	Able-bodied	104	M	49	Classical	23	Short	10	4
							Middle	15	19
					Freestyle	26	Short	10	8
							Middle	15	18
			F	55	Classical	17	Short	5	3
							Middle	10/15	14
					Freestyle	38	Short	5	9
							Middle	10/15	29

Female skiers (F), Male skiers (M)

Table 5. Category, class, age, body-mass, and training volume (mean ± SD) of the four Para and seven able-bodied skiers included in Study II and the supplementary analyses.

Parameter	Study II				
	Para			Able-bodied	
	F (n=1)	F (n=1)	M (n=2)	F (n=4)	M (n=3)
Category	Sitting	Standing	VI		
Class	LW11	LW4	B3		
Age (years)	33.0	19.0	24.0 ± 2.8	23.5 ± 1.3	25.0 ± 1.5
Body-mass (kg)	60.0	61.0	70.5 ± 1.9	63.5 ± 4.1	83.0 ± 2.0
Weekly training (hours)	22 ± 7	11.0	13.5 ± 5.0	14.5 ± 1.0	16.2 ± 1.0

Female skiers (F), Male skiers (M), Visually impaired (VI)

Table 6. Age, body-mass, and training volume (mean ± SD) of the fifteen male able-bodied skiers included in Study III and supplementary analyses.

Parameter	Study III
	Able-bodied
	M (n=15)
Age (years)	25.0 ± 4.0
Body-mass (kg)	79.0 ± 6.0
Weekly training (hours)	9.3 ± 3.0

Male skiers (M)

The seven elite able-bodied skiers in Study II were four female skiers and three male skiers from the Norwegian B national team, and they served as a reference group for the Para skiers. The fifteen upper-body trained male able-bodied skiers in Study III were chosen in order to reduce high within-group differences in maximal power output and aerobic capacity previously found in sitting skiers with different disabilities,[125, 149] as well as to ensure sufficient numbers of participants were included in the study. Nevertheless, the findings may serve as reference data for future research on sitting skiers. The elite Para and able-bodied skiers in Study II were recruited through the Norwegian national cross-country skiing team and the regional center (Mid-Norway) of the Norwegian Olympic Sports Center (Olympiatoppen). The able-bodied skiers in Study III were recruited through collaboration with the Centre for Elite Sports Research (SenTIF), at the Norwegian University of Science and Technology (NTNU). For Study I, the IPC and FIS obtained informed consent from all competing athletes prior to publication of race data online. The data were obtained prior to any processing to remove identifying information. All participants in Study II and III signed an informed consent form and were made aware that they could withdraw from the respective studies at any point without the need to provide an explanation. The data extraction and processing (Study I) and experimental studies (Study II and III) were approved by the Norwegian Centre for Research Data (NSD) and the studies conducted in line with the Declaration of Helsinki (1964).

3.3 DATA EXTRACTION

Study I. Data for each male and female Para and able-bodied skier were extracted for every short- and middle distance, time-trial cross-country skiing races in the classical and freestyle skiing technique. The data included sex, race time, final rank, race distance, skiing technique, event type, and season for each skier. For the Para skiers, the data also included the skiing category and class. The unadjusted race times were obtained by dividing each adjusted race time by the class-specific time factor used during the 2019–2020 season.

3.4 TEST PROTOCOL/MEASUREMENTS

Study II. The Para and able-bodied skiers performed a time-trial cross-country skiing race on snow, using the classical skiing technique (Figure 10). The female LW4 skier and able-bodied skiers raced 10 km (four laps) and the male B3 skiers and able-bodied skiers raced 15 km (six laps) on a 2.5 km racecourse (Figure 11). The LW11 sit-skier raced 5.6 km on a 0.93 km racecourse (six laps), where two parts of the racecourse overlapped with the racecourse used by the female LW4, male B3 skiers, and able-bodied skiers (Figure 11). During each race, the time, positioning, altitude, and movement data of each Para skier and able-bodied skier were continuously tracked with a Catapult device with integrated GNSS and IMU, which was positioned in a tight fitting vest on the skier’s upper back, under the race bib.

Figure 10. The female LW4 skier (left) and one of the male B3 skiers together with his guide (yellow race bib) (left) during the classical cross-country skiing race.

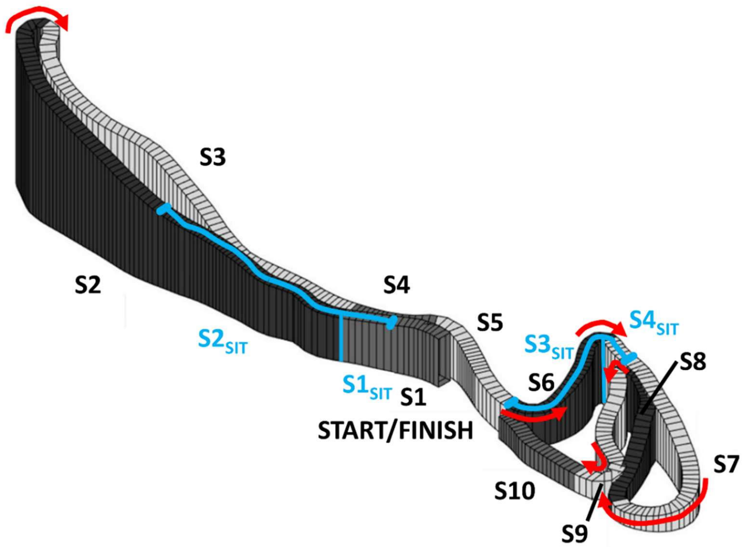
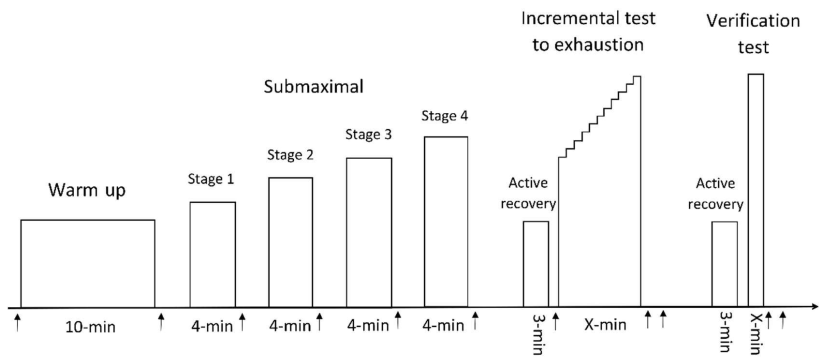


Figure 11. The 2.5 km cross-country skiing racecourse divided into the ten sections according to the altitude, including three uphill (black), three flat (dark gray), and four downhill (light gray) sections. Two parts of the course are used by both the female LW11 sit-skier, the female LW4 skier, and the female able-bodied skiers (one flat ($S1_{SIT}$), two uphills ($S2_{SIT}$, $S3_{SIT}$), and one downhill ($S4_{SIT}$) sections, blue lines). Six turns were distributed over the 2.5 km lap (red arrow). With different placement of the start and finish, there was a gap in the 2.5 km racecourse that was left out of the analyses. Section (S) (length [meter], incline range [%]); S1: 131 m, −2.6–1.6%; S2: 543 m, 1.7–12.4%; S3: 509 m, −11.7–0.2%; S4 100 m, 0.7–2.8%; S5: 156 m, −6.0–0.0%; S6: 166 m, 1.3–12.7%; S7: 339 m, −8.5– (−0.4)%; S8: 200 m, 1.2–16.0%; S9: 183 m, −10.1–(−1.0)%; S10: 138 m, 0.0–1.6%. $S1_{SIT}$: 70 m, −2.5–1.7%; $S2_{SIT}$: 180 m, 2.3–5.7%; $S3_{SIT}$: 173 m, −1.5–12.7%; $S4_{SIT}$: 57 m, −3.1– (−0.9)%.

Study III. The two upper-body double poling cross-country sit-skiing test sessions were counterbalanced by the incline of 0.5% (FLAT; submaximal speeds 10, 12, 14, and 16 km·h^{-1}) or 5% (UPHILL; submaximal speeds 4, 5, 6, and 7 km·h^{-1}), each comprising four submaximal stages with increasing speed, an incremental test to exhaustion, and a verification test (Figures 12, 13, and 14). Strong verbal encouragement was used during both the incremental test to exhaustion and the verification test. The verification test was used to confirm that the highest $\dot{V}O_{2peak}$ had been reached in the incremental test to exhaustion despite a longer duration spent at the highest workload reached in the incremental test.[150]



			Warm up / active recovery	Stage 1	Stage 2	Stage 3	Stage 4	Incremental	Verification
Counter-balanced by incline	FLAT	Incline (%)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
		Velocity (km·h^{-1})	8-10	10	12	14	16	14 →	Highest reach from incremental
	UPHILL	Incline (%)	0.5	5	5	5	5	5	5
		Velocity (km·h^{-1})	8-10	4	5	6	7	6 →	Highest reach from incremental

Figure 12. Test protocol for submaximal and maximal intensity during upper-body double poling cross-country sit-skiing for the fifteen able-bodied skiers. The protocol was completed twice: one day of 0.5% incline (FLAT) and one day of 5% incline (UPHILL), with the order of incline counterbalanced between the skiers. Black vertical arrow indicates blood sample.

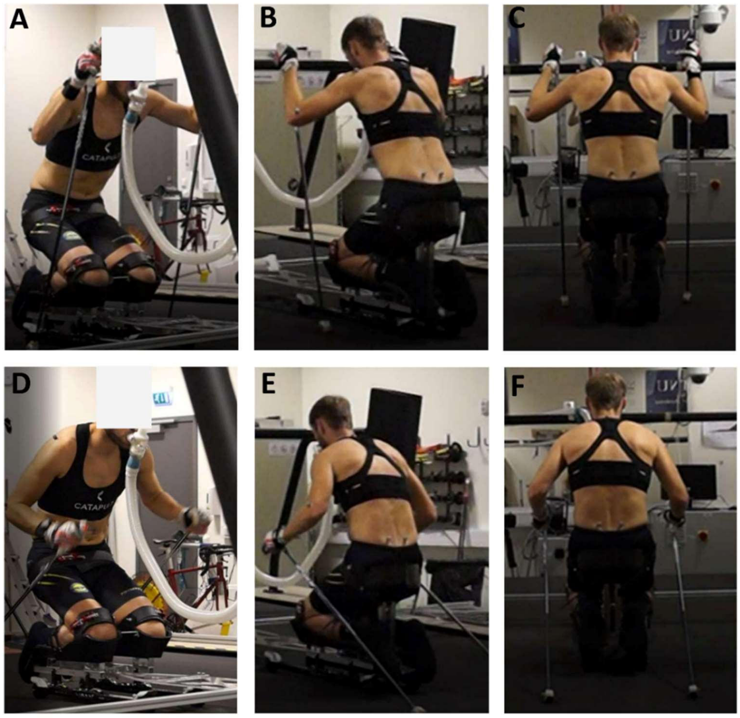


Figure 13. A skier upper-body double poling cross-country sit-skiing on a treadmill (Study III). Obliquely from the front (A and D), obliquely from the side (B and E), and from behind (C and F) in the beginning (A, B, and C) and the end (D, E, and F) of the poling phase.

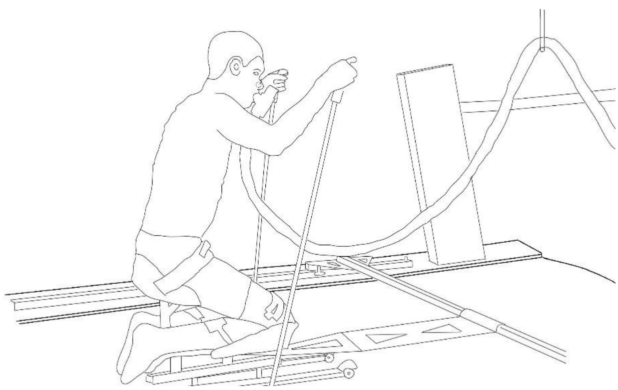


Figure 14. Test setup on the treadmill. The cross-country sit-ski was mounted on a pair of classical roller-skis, with a “kneeing” sitting position and adjustable straps around the hips, thighs, and lower legs to secure the skier to the sit-ski. The front of the sit-ski was firmly attached to an aluminum crossbar of a custom made safety system, connected to rails on each side of the treadmill, allowing the crossbar to move in the same direction as the sit-ski.

3.5 INSTRUMENTS AND MATERIALS

Study II. Each Para and able-bodied skier was tracked with a Catapult device (OptimEye S5, Catapult Innovations, Melbourne, Australia), consisting of a 10 Hz GNSS device and IMU combined of a 100 Hz triaxial accelerometer and gyroscope sensor (Figure 15). To ensure GNSS lock and acquisition of the satellite signals the Catapult device were placed outside in an open space for a minimum of 10 min. Each skier used its own equipment, including skis, poles, boots, sledge for the sit-skier, and ski base material (i.e., grinds, structure, and waxing), according to the daily conditions and individual preferences.

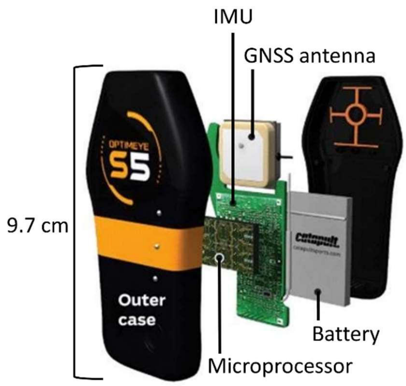


Figure 15. Catapult device with integrated global navigation satellite system (GNSS) and an inertial measurement unit (IMU). The GNSS antenna receives signals from GPS and GLONASS space-based satellites for twice the tracking. The IMU is combined of a (1) gyroscope sensor, which measure the orientation of the skier's body position, (2) accelerometer, which measure impact forces, (3) magnetometer, which measure direction. The microprocessor crunches the data for preparation prior to analyses.

Study III. Respiratory variables (oxygen uptake ($\dot{V}O_2$), respiratory exchange ratio (RER), and minute ventilation (VE)) were measured continuously throughout both test sessions employing open-circuit indirect calorimetry (Oxycon Pro; Jeager GmbH, Hoechberg, Germany). Prior to each test session, the O_2 and CO_2 analyzers were calibrated using a mixture of gases (15.0 ± 0.04% O_2 and 5.0 ± 0.1% CO_2; Riessner-Gase GmbH & Co, Lichtenfels, Germany) and the expiratory flow meter was manually calibrated with a 3 L syringe (Hans Rudolph Inc, Kansas City, MO). The heart rate (HR) was continuously measured with a HR10 heart rate monitor (Polar Electro), which was connected to a Polar V800 watch (Polar Electro OY, Kempele, Finland). Capillary blood samples (20 µL) obtained after each submaximal stage (one sample, 1 minute) and two samples (1 minute and 3 minute) after both the incremental test and verification test were analyzed for BLa using the Biosen C-Line lactate analyzer (Biosen, EKF Industrial Electronics, Magdeburg, Germany). The rating of perceived total exertion, muscular exertion, and ventilatory exertion (RPE_T, RPE_M, and RPE_V, respectively) was recorded after each submaximal stage, the incremental test, and the verification test based on the Borg scale (6–20).[137]

All tests were performed with the same cross-country sit-ski (SKENO, Oslo, Norway), which was attached to the same pair of classical roller-skis (resistance category 2, μ = 0.018; IDT Sports, Lena, Norway), on a 5 × 3-m motor-driven treadmill (Forcelink B.V., Culemborg, The Netherlands). The skiers used a "kneeing" sitting position with individual adjustments using adjustable straps around the hips, thighs, and lower legs (Figure 14). This "kneeing" sitting position is mainly utilized by Para skiers who have full trunk control (i.e., LW11.5, and LW12) (Figure 2 and Table 1).[109, 132, 133] For safety, a custom made system attached the sit-ski to rails on each side of the treadmill using an aluminum crossbar (Figure 14). The skiers used Swix Triac 3.0 junior poles (Swix, Lillehammer, Norway) with specialized carbide tips for treadmill roller-skiing.

Nine infrared Oqus 400 cameras (Qualisys AB, Gothenburg, Sweden) captured 3-dimensional position characteristics with a sampling frequency of 250 Hz toward the end of each submaximal stage (two x 30-second) and during each minute in the incremental test (one x 30-second). In total it was placed 8 reflective markers (spherical, ø 16 mm) on the equipment: two markers on each pole (one around 5 cm below the bottom of the grip handle and one on the lateral side of the carbide tip), and two markers on each ski (one 1 cm behind the front wheel and one 1 cm in front of the back wheel). Prior to each test session, the camera system was calibrated according to the manufacturer's specifications.

3.6 DATA PROCESSING AND CALCULATIONS

The data processing in the three studies was performed using Microsoft Office 2016 Excel (Microsoft Corporation, Redmond, WA, USA). Additionally, for data processing and calculations Stata 16.1 (StataCorp LLC, College Station, TX, USA) was used in Study I, and MATLAB R2018a (version 9.7.0.1190202, Math-Works, Natick, MA) was used in Study II.

Study I. To calculate the RT_{diffs} of the top 3 and top 8 skiers, only races with >10 competitors were included. For each included race, the percent RT_{diffs} were calculated for each ranking compared with the winner (top 3 skiers: second to third; top 8 skiers: second to eight). For the Para skiers, the percent RT_{diffs} were calculated using both the adjusted and unadjusted race times (adjusted RT_{diffs} and unadjusted RT_{diffs}, respectively). The distribution of classes was found by counting the number of skiers in each class for female and male top 3 and top 8 Para skiers for both the adjusted and unadjusted race times. Additionally, to gain an overview, the classes were further grouped into higher (VI: B2 and B3; Standing: LW4 and LW8; Sitting: LW12), middle (Standing: LW6 and LW9; Sitting: LW11 and LW11.5), and lower (VI: B1; Standing: LW2, LW3, and LW5/7; Sitting: LW10 and LW10.5) classes to compare whether the distribution of skiers in those groups changed between adjusted and unadjusted race times. The division into the higher, middle, and lower classes is not recognized by the IPC as a standardized division, but it was used for simplification purposes.

Study II. Based on the positioning and altitude data obtained from the GNSS, the racecourse was divided into ten sections for the female LW4 skier, the male B3 skiers, and able-bodied skiers, with three uphill, three flat, and four downhill sections (Figure 11). The two parts of the racecourse that were overlapping for the female LW11 sit-skier, the female LW4 skier, and female able-bodied skiers, were for the descriptive comparison between these skiers divided into one flat section, two uphill sections, and one downhill section (Figure 11). The speed data were obtained from the time differentiation of the position data. For the LW4 skier, B3 skiers, and able-bodied skiers, the time and speed over the four or six laps were averaged for the further analyses. In the comparison between the Para (the LW4 and B3 skiers) and able-bodied skiers, average values of time and speed were used for each group of female and male able-bodied skiers (Study II). For the female LW11 sit-skier, the female LW4 skier, and the female able-bodied skiers, the time and speed of the two overlapping parts over the six and four laps were averaged for further analyses. The average values of time and speed were used for the group of female able-bodied skiers.

Automatic sub-technique classification was carried out by using the movement data relating to the female LW4, male B3 skiers, and able-bodied skiers, as measured by IMUs. Since sit-skiers only utilize the DP technique, no sub-technique classification was done for the female LW11 sit-skier. To apply the framework and accompanying algorithms for Para skiers with a similar degree of accuracy as that for able-bodied skiers, for whom there was a 96% classification accuracy per distance, a visual examination of the automatic classification was done. After visual assessment, around 10% of the cycles were manually corrected for the Para skiers and reached a relatively similar classification accuracy as that for able-bodied skiers. The sub-techniques were classified as DP, DK, DIA (including both DIA and herringbone (HRB)), and OTHER. The sub-technique classed as OTHER almost entirely consisted of the tuck position at higher speeds (7–10 $m \cdot s^{-1}$), but at lower speeds (2.5–6.5 $m \cdot s^{-1}$) also turn techniques and cycles that did not fulfil the above-specified criteria were included.

Study III. For the incremental and verification test, 30-second (with a 10-second data window) moving averages were calculated for the respiratory variables and 3-second moving averages for HR. The peak responses were determined from the highest respiratory values, HR, and RPE reached during either the incremental test or the verification test. Metabolic rate (MR) during submaximal WRs and peak metabolic rate (MR_{peak}) were calculated from $\dot{V}O_2$ and $\dot{V}O_{2peak}$, associated measurements of RER, and a standard conversion table, respectively.[151] Submaximal WR and WR_{peak} were calculated as the sum of power against gravity, rolling friction, and rail friction for all the work intensities (i.e., four submaximal and one maximal intensity). Submaximal GE was calculated as the ratio of the submaximal values of WR and MR, without any baseline subtraction.[152]

From the kinematic data, recorded using Qualisys Track Manager (version 2019.3; Qualisys AB) and processed using MATLAB R2019b (version 9.7.0.1190202, MathWorks, Natick, MA), cycle characteristics were calculated. Cycle time (CT) was calculated as the time between two coinciding starts of pole-belt contacts and cycle rate (CR) as the reciprocal of CT. The PT was defined as the period with continuous pole-belt contact, and swing time (ST) as the period without pole-belt contact. Relative PT and ST were calculated as the percentage of CT. The work per cycle ($work_{cycle}$) was calculated as WR multiplied by CT. Cycle length (CL) was calculated as the product of the cycle mean sit-ski velocity and CT.

For each skier, the relationship between the absolute submaximal WR and the dependent variables was determined by linear regression analyses for the physiological variables, RPE, MR, and GE, and by exponential regression analyses for BLa. Values of the dependent variables at a given absolute WR (60, 80, and 100 W) were calculated to compare FLAT and UPHILL at identical WRs by using interpolation and extrapolation from the regression analyses. In supplementary analyses, for each skier, the relationship between RPE_T (i.e., the overall perceived effort) and the dependent variables (RPE_M, RPE_V, $\%HR_{peak}$, and $\%\dot{V}O_{2peak}$) was determined by linear regression analysis, and by exponential regression analysis for BLa. Values of the dependent variables at a given absolute RPE_T were calculated to compare FLAT and UPHILL at identical RPE_T at low, moderate, and high RPE_T (i.e., 11, 13, 14, 16, 17, and 20) by using interpolation and extrapolation from the regression analyses.

3.7 STATISTICAL ANALYSIS

For the statistical tests in Study I and III, an alpha level of 0.05 was used to indicate statistical significance. The analysis of the statistics was performed using Stata 16.1 (StataCorp LLC, College Station, TX, USA) for Study I and IBM SPSS Statistics (version 24.0; SPSS Inc, Chicago, IL) for Study III.

Study I. For the first aim of the study, we investigated, with linear mixed modeling, the main effect of skiing group (i.e., VI, standing, sitting, and able-bodied skiers) and sex, as well as the interaction between skiing group*sex on RT_{diffs} for the top 3 and top 8 skiers. In the latter analyses, the adjusted RT_{diffs} were used for the Para skiers. For the Para cross-country skiing groups, separate analyses were performed to investigate whether the adjusted and unadjusted RT_{diffs} differed. For the second aim of the study, we used linear mixed modeling to investigate the main effect of skiing group and season, as well as the interaction between skiing group*season on RT_{diffs} for top 3 and top 8 skiers. Also, in the latter analyses, the adjusted RT_{diffs} were used for the Para skiers. For the Para cross-country skiing groups, separate analyses were performed to investigate whether the unadjusted RT_{diffs} were larger between seasons than the adjusted RT_{diffs}. All models were adjusted for the fixed factors skiing technique (classical or freestyle), distance (short or middle), and event type (World Cup, World Championship, or PWG/OWG). Post-hoc analyses using the Bonferroni method were performed for pairwise comparisons of the estimated marginal means for the skiing group, skiing group*sex, and skiing group*season. Visual examination of Q-Q plots, and plots that compared residual versus predicted values did not indicate any deviation from normality. The results are presented as mean ± 95% confidence interval (CI), unless stated otherwise. Furthermore, to investigate whether differences race times were related to the distribution of classes, a Fisher's exact test was performed for each female and male Para cross-country skiing category to compare the overall distribution of classes between the adjusted and unadjusted race times for top 3 and top 8 skiers. Post-hoc tests with Bonferroni correction were performed for pairwise comparisons of the number of skiers in each class between adjusted and unadjusted race times for the top 3 and top 8 skiers. Additionally, pairwise comparisons of the number of skiers in higher, middle, and lower classes were performed between adjusted and unadjusted race times.

Study II. In the case series, descriptive comparisons were made for time, speed, and sub-technique distribution between the Para skiers and able-bodied skiers, to demonstrate the feasibility of the framework based on micro-sensor technology for future use in investigations of performance in Para cross-country skiing.

Study III. A linear mixed model with fixed coefficients and random intercept was used to investigate the main effect of incline and WR for each dependent variable (physiological variables, RPE, and cycle characteristics), as well as the interaction between incline*WR during the submaximal stages. A linear mixed model with fixed coefficients and random intercept was employed to investigate the main effect of incline and RPE_T for each dependent variable (RPE_M, RPE_V, $\%HR_{peak}$, $\%\dot{V}O_{2peak}$, and BLa), as well as the interaction between incline*RPE_T at low, moderate, and high intensity. For every dependent variable at each absolute WR, we performed post hoc tests with Bonferroni correction for pairwise comparisons between FLAT and UPHILL. For every dependent variable at each RPE_T, post hoc tests with Bonferroni correction were performed for pairwise comparisons between FLAT and UPHILL. Additionally, descriptive comparisons were made for RPE, BLa, $\%HR_{peak}$, and $\%\dot{V}O_{2peak}$ between sit-skiing and able-bodied cross-country skiing, on which the standardized intensity scale is based on (Figure 7). Paired sample *t* tests were performed to investigate differences in peak values between FLAT and UPHILL.

4 RESULTS

4.1 STUDY I
Comparison of Race Time-differences between and within Para and Able-Bodied Cross-Country Skiers

4.1.1 DIFFERENCES IN RACE TIMES ACROSS SKIING GROUPS AND SEX

When adjusted for sex, significantly larger RT_{diffs} were displayed by the Para skiers compared with the able-bodied skiers (top 3: 2.1% vs. 0.9%; top 8: 6.2% vs. 2.1%, all $p < 0.01$). Across the Para cross-country skiing categories (i.e., VI, standing, and sitting skiers), RT_{diffs} displayed by the top 3 skiers were not significantly different (all $p > 0.2$). However, RT_{diffs} displayed by the top 8 skiers were significantly larger for VI compared with standing and sitting (7.0%, 5.5%, and 5.6%, respectively; all $p < 0.05$) (Figure 16).

When adjusted for skiing groups, significantly larger RT_{diffs} were displayed by the female skiers compared with male skiers (top 3: 1.8% vs. 1.3%; top 8: 4.9% vs. 3.5%, all $p < 0.05$) (Figure 16). RT_{diffs} displayed by the top 3 skiers were significantly larger for female able-bodied skiers compared with male able-bodied skiers (1.3% vs. 0.6%, $p < 0.02$), while RT_{diffs} were not significantly different between sexes within any of the Para cross-country skiing categories (all $p > 0.1$). For the top 8 skiers, RT_{diffs} were significantly larger for female sitting skiers compared with male sitting skiers (7.0% vs. 4.5%, $p < 0.001$) and able-bodied (2.8% vs. 1.6%, $p < 0.001$) skiers.

Neither the top 3 skiers nor top 8 skiers displayed any significant differences between adjusted and unadjusted RT_{diffs} in any of the Para cross-country skiing categories (all $p > 0.1$) (Figure 16).

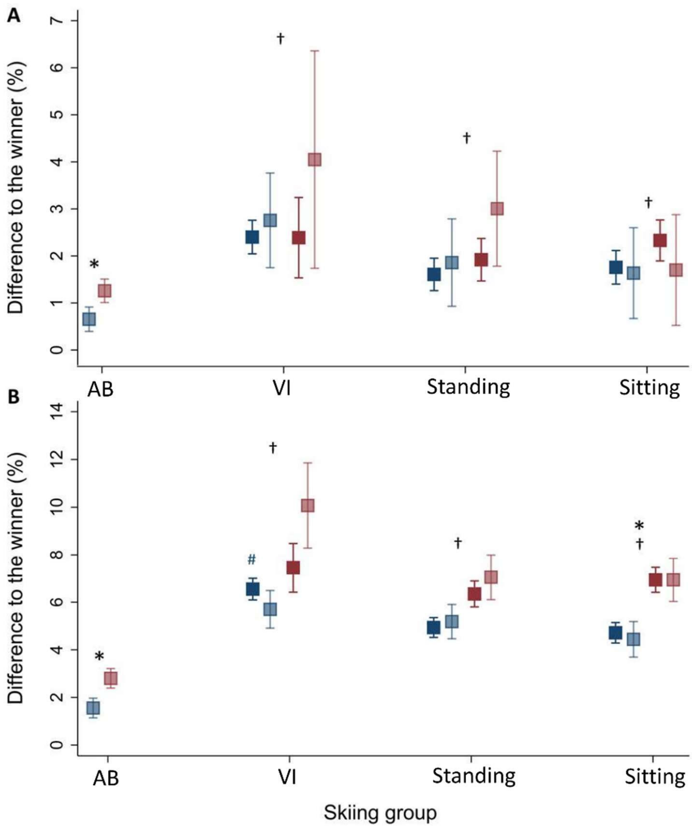


Figure 16. Estimated adjusted (dark color) and unadjusted (light color) differences in race time (RT_{diffs}) for (A) top 3 and (B) top 8 female (red) and male (blue) Para skiers (VI: visually impaired standing skiers; Standing: physically impaired standing skiers; Sitting: physically impaired sitting skiers) and able-bodied (AB) skiers. Presented as mean ± 95% confidence interval. *Significantly larger RT_{diffs} for female skiers compared with male skiers within same skiing group, $p < 0.05$. †Significantly different from able-bodied skiers, $p < 0.01$. #Significantly different from male standing and sitting skiers, $p < 0.05$.

4.1.2 DIFFERENCES IN RACE TIMES ACROSS SEASONS

Adjusted for sex and skiing group, neither the top 3 skiers nor top 8 skiers displayed RT_{diffs} that differed significantly across the 2011–2020 seasons (top 3: VI: 3.6–2.6%, standing: 2.2–1.6%, sitting: 1.0–3.9%, able-bodied: 1.0–1.1%); top 8: VI: 12.0–4.2%, standing: 2.6–3.5%, sitting: 1.9–5.9%, able-bodied: 1.5–0.9%, all $p > 0.1$) (Figure 17). Hence, the comparisons between skiing groups and sex were similar across seasons, which meant that the results of comparisons performed with pooled RT_{diffs} across seasons (i.e., described in the preceding subchapter, 4.1.1) were reliable. Furthermore, neither the top 3 nor the top 8 skiers displayed a significant difference between adjusted and unadjusted RT_{diffs} across the 2011–2020 seasons (all $p > 0.1$) (Figure 17).

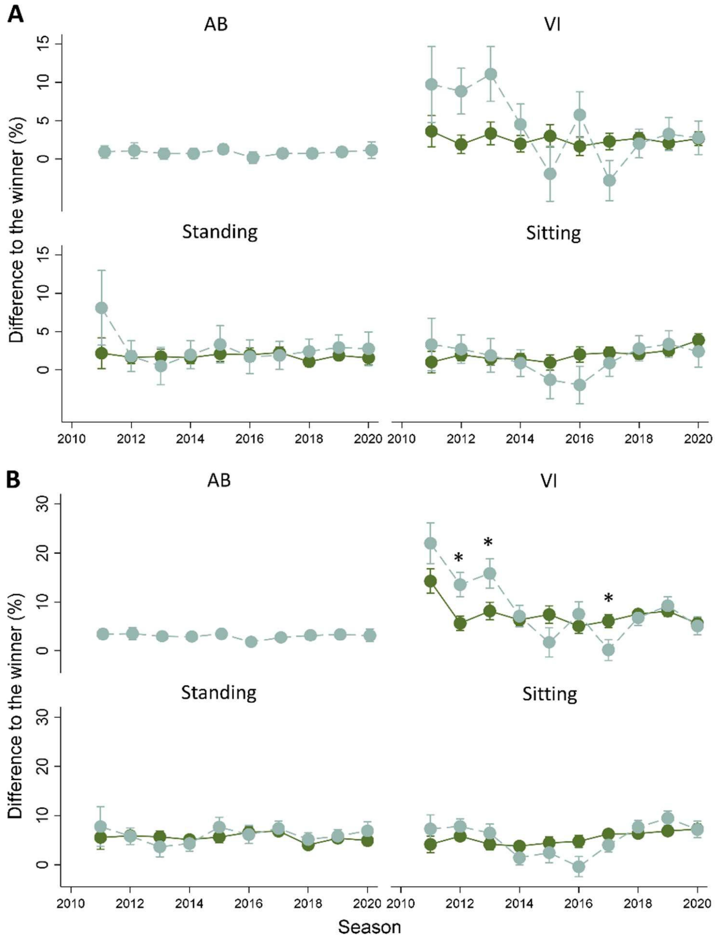


Figure 17. Estimated differences in race time (RT_{diffs}) for (A) top 3 and (B) top 8 of adjusted (dark green, solid line) and unadjusted (light green, dashed line) race times of Para skiers (VI: visually impaired standing skiers; Standing: physically impaired standing skiers; Sitting: physically impaired sitting skiers), and able-bodied (AB) skiers for the 2011-2020 seasons. Values presented as an annual average ± 95% confidence interval. *Significantly different from unadjusted RT_{diffs}, $p < 0.05$.

4.1.3 CLASS DISTRIBUTION BETWEEN ADJUSTED AND UNADJUSTED RACE TIMES

There was a significant decrease in the proportion of skiers in the higher classes among top 3 female standing and sitting skiers (all $p < 0.004$) and the top 3 and top 8 male VI, standing, and sitting skiers (all $p < 0.005$) (Figures 18 and 19) after time factor adjustment. For the top 3 female VI skiers and the top 8 female VI, standing, and sitting skiers, there was no significant change in the distribution of skiers in the higher classes between the adjusted and unadjusted race-times (all $p > 0.06$) (Figure 18). There was a significant increase of the proportion of skiers in the lower classes after time factor adjustment among the top 3 and top 8 male VI, standing, and sitting skiers (all $p < 0.000$) (Figures 18 and 19). No significant change was found in the distribution of skiers in the lower classes between the adjusted and unadjusted race-times for the top 3 and top 8 female VI, standing, and sitting skiers (all $p > 0.05$) (Figure 18).

For the adjusted race times, there was a significantly larger proportion of skiers in the higher classes and significantly smaller proportion of skiers in the lower classes among the top 3 female VI skiers and top 8 female VI and standing skiers compared with their male counterparts (all $p < 0.01$).

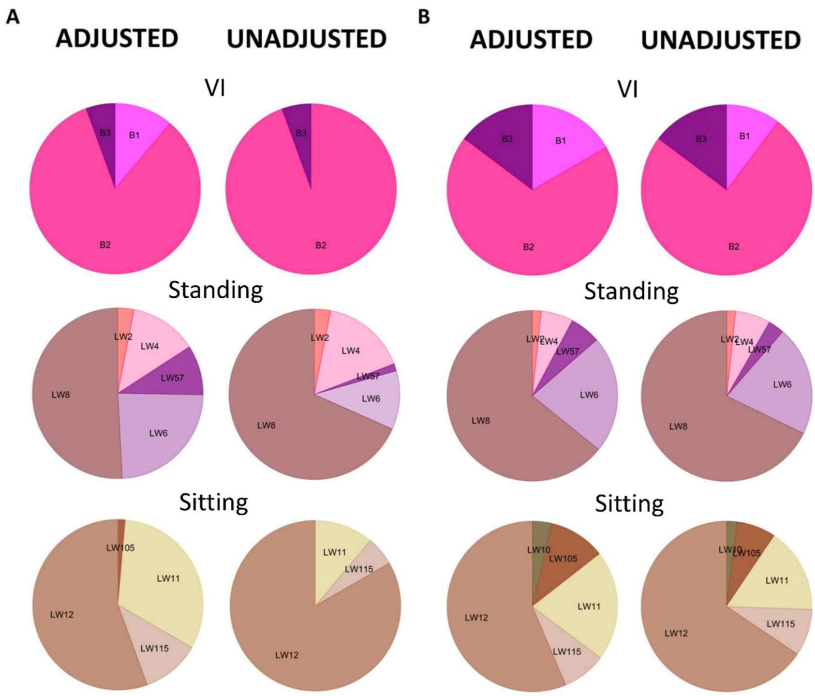


Figure 18. The distribution of classes for the top 3 (A) and top 8 (B) female sitting, standing, and VI skiers for adjusted and unadjusted race-times. See Table 1 for an overview of the Para cross-country skiing categories and classes.

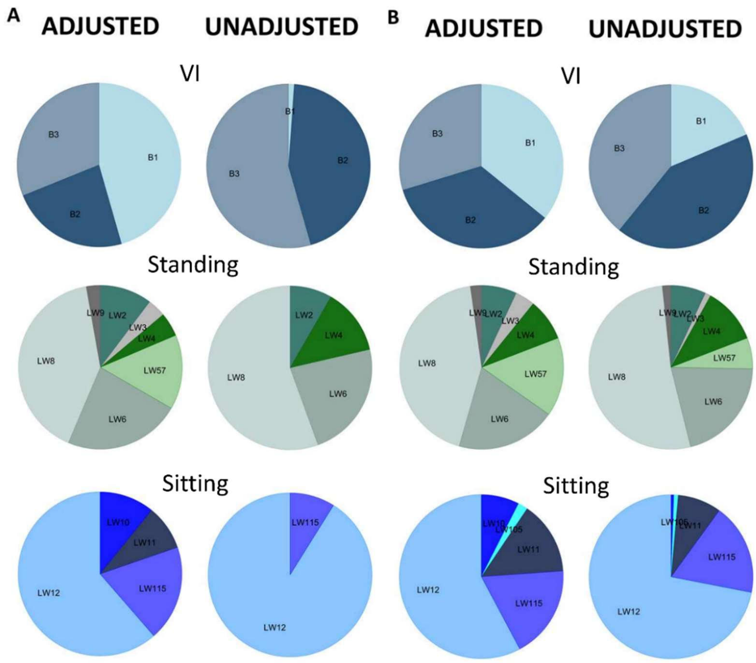


Figure 19. The distribution of classes for the top 3 (A) and top 8 (B) male sitting, standing, and VI skiers for adjusted and unadjusted race-times. See Table 1 for an overview of the Para cross-country skiing categories and classes.

4.2 STUDY II

Framework for In-Field Analyses of Performance and Sub-Technique Selection in Standing Para Cross-Country Skiers

4.2.1 PERFORMANCE

The speed fluctuation pattern was similar throughout the race for both the Para skiers (the LW4 and B3 skiers) and the able-bodied skiers, but in general the Para skiers had slower skiing speeds (Figures 20 and 21; Table 7). The female LW4 skier completed with a 4.26-minute slower race time than the female able-bodied skiers, and the male B3a and B3b skiers completed with a 7.21-minute and a 12.47-minute slower race time, respectively, compared with the male able-bodied skiers. Furthermore, compared with the female and male able-bodied skiers, the female LW4 skier and male B3 skiers displayed 14% and 19% slower average speeds, respectively, with the largest time loss (35±6 and 65±36 seconds per lap) in uphill terrain (Figures 20 and 21; Table 7). The largest relative speed difference between the female LW4 skier and female able-bodied skiers, and between the male B3 skiers and male able-bodied skiers was displayed in uphill and flat terrain, followed by downhill terrain (Figures 20 and 21; Table 7).

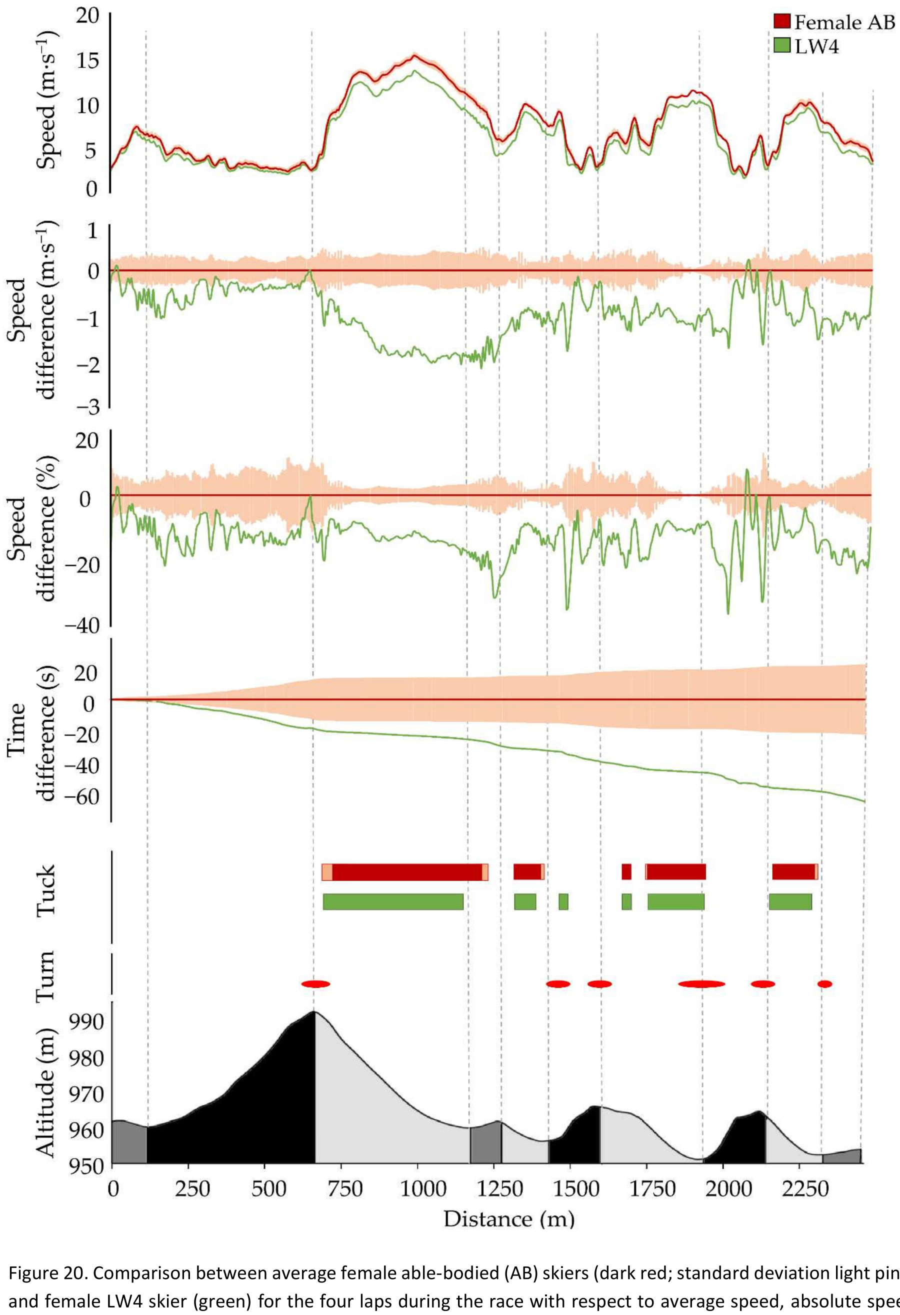


Figure 20. Comparison between average female able-bodied (AB) skiers (dark red; standard deviation light pink) and female LW4 skier (green) for the four laps during the race with respect to average speed, absolute speed difference, relative speed difference, accumulated time difference, and tuck. Course details are visualized in the lower part of the figure; turns (red dashes) and altitude profile of the 2.5 km racecourse, with uphill (black), flat (dark gray), and downhill (light gray) sections.

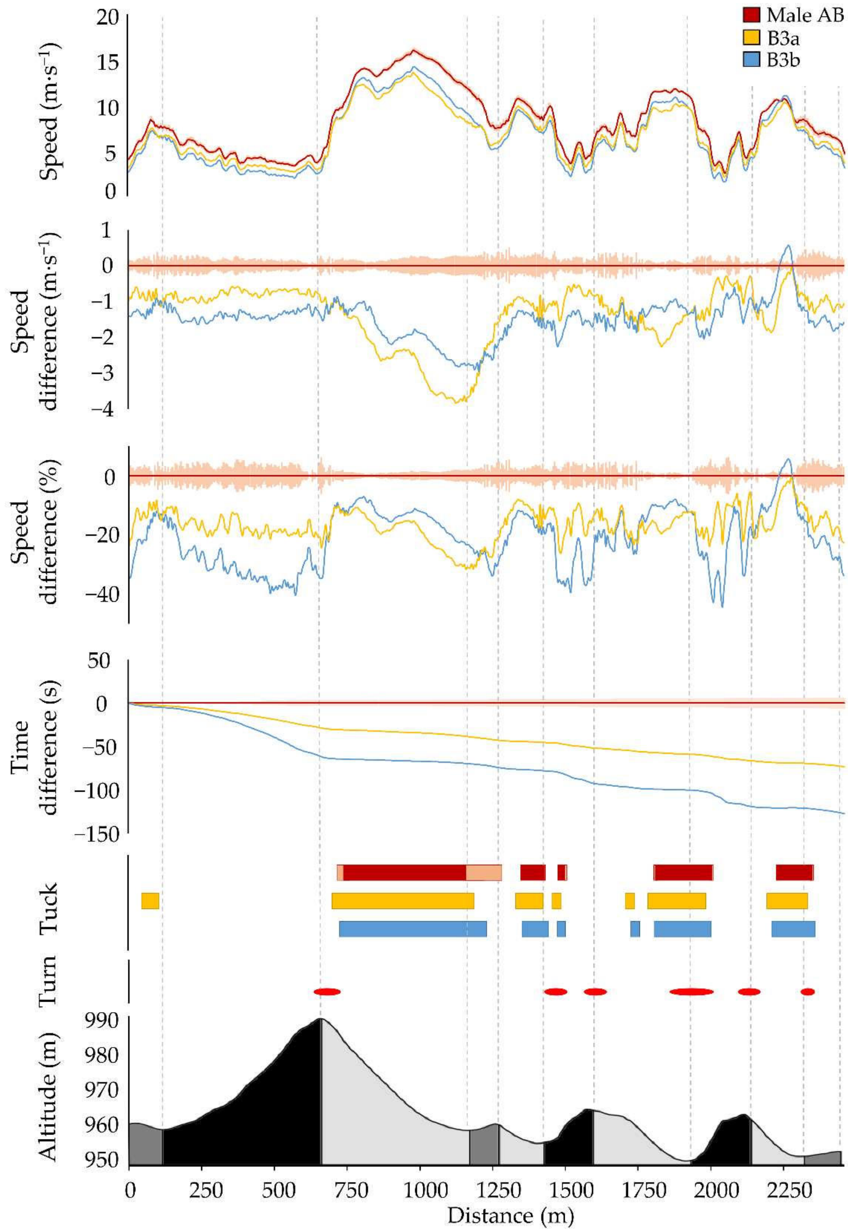


Figure 21. Comparison between average male able-bodied (AB) skiers (dark red; standard deviation light pink), the male B3a skier (yellow), and the male B3b skier (blue) for the six laps during the race with respect to average speed, absolute speed difference, relative speed difference, accumulated time difference, and tuck. Course details are visualized in the lower part of the figure; turns (red dashes) and altitude profile of the 2.5 km racecourse, with uphill (black), flat (dark gray), and downhill (light gray) sections.

Table 7. Proportion of skiing time in different terrains (%), absolute average speed ($m \cdot s^{-1}$), relative speed difference (% of able-bodied skiers), and time loss relative to able-bodied skiers of same sex per lap (seconds) for the female LW4 skier, the male B3 skiers, and the female and male able-bodied skiers.

	Terrain	**LW4**	**Female able-bodied**	**B3a**	**B3b**	**Male able-bodied**
Proportion of time in different terrains (%)	Uphill	57	58 ± 16	54	59	54 ± 14
	Flat	15	14 ± 1	14	14	14 ± 1
	Downhill	28	28 ± 3	31	27	32 ± 3
Absolute average speed ($m \cdot s^{-1}$)	Overall	6.0 ± 2.3	6.9 ± 2.6	6.7 ±	6.4 ± 2.4	7.9 ± 2.6
	Uphill	3.7 ± 0.5	4.3 ± 0.6	4.6 ± 0.6	3.9 ± 0.5	5.3 ± 0.6
	Flat	5.1 ± 0.7	6.2 ± 1.2	6.0 ± 0.6	5.7 ± 0.8	7.5 ± 1.4
	Downhill	8.3 ± 1.6	9.5 ± 1.9	8.7 ± 1.2	8.9 ± 1.5	10.3 ± 1.9
Relative speed difference (% of able-bodied skiers)	Overall	14 ± 4	100	16 ± 5	20 ± 7	100
	Uphill	14 ± 2	100	14 ± 2	26 ± 3	100
	Flat	16 ± 8	100	19 ± 7	24 ± 4	100
	Downhill	12 ± 1	100	15 ± 4	14 ± 5	100
Time loss per lap (seconds)	Overall	65 ± 10		72 ± 7	126 ± 17	
	Uphill	35 ± 6		13 ± 11	30 ± 24	
	Flat	11 ± 3		4 ± 1	5 ± 1	
	Downhill	19 ± 2		6 ± 4	5 ± 3	

Compared with the female LW4 skier and the female able-bodied skiers, the female LW11 sit-skier displayed in the overlapping parts of the racecourse a 7% and 22% slower average speed, respectively for the first ($S1_{SIT}$ + $S2_{SIT}$) and second ($S3_{SIT}$ + $S4_{SIT}$) part, with the largest time loss in the uphill terrain (7 seconds and 19 seconds per lap, respectively) (Figure 22; Table 8). The largest relative speed difference between the female LW11 sit-skier, the female LW4 skier, and female able-bodied skiers was displayed in uphill terrain (Figure 22; Table 8).

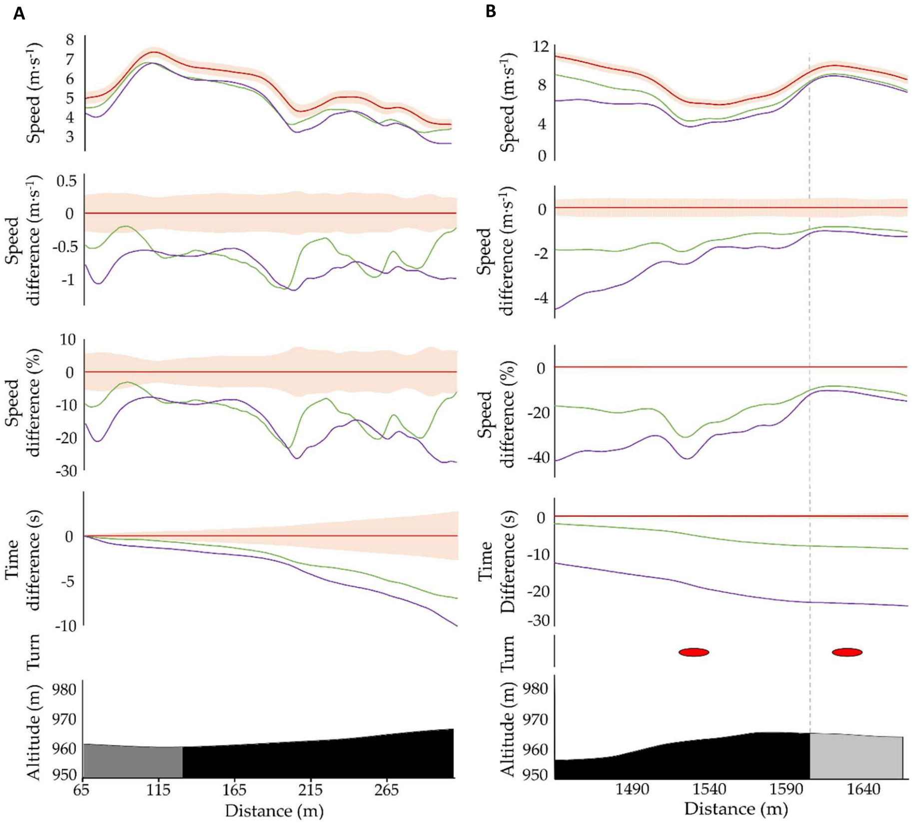


Figure 22. Comparison between average female able-bodied skiers (dark red; standard deviation light pink), female LW4 skier (green), and female LW11 sit-skier (purple) for the two overlapping parts of the racecourse (A: $S1_{SIT}$ and $S2_{SIT}$; B: $S3_{SIT}$ and $S4_{SIT}$) for the four (able-bodied and LW4 skiers) and six (LW11 skier) laps with respect to average speed, absolute speed difference, relative speed difference, accumulated time difference, and tuck. Course details are visualized in the lower part of the figure; turns (red dashes) and altitude profile, with uphill (black), flat (dark gray), and downhill (light gray) sections.

Table 8. Proportion of skiing time in different terrains (%), absolute average speed ($m \cdot s^{-1}$), relative speed difference (%), and time loss relative to the female able-bodied skiers per lap (seconds) for the female LW11 sit-skier, female LW4 skier, and female able-bodied skiers.

	Terrain	LW11	LW4	Female able-bodied
Proportion of time in the different terrains (%)	Uphill	80	79	78
	Flat	12	12	13
	Downhill	8	9	9
Absolute average speed ($m \cdot s^{-1}$)	Overall	5.4 ± 1.1	5.9 ± 1.5	6.9 ± 2.1
	Uphill	4.8 ± 0.7	5.4 ± 1.3	6.5 ± 2.0
	Flat	5.6	5.8	5.1 ± 0.3
	Downhill	8.2	8.4	9.3 ± 0.2
Relative speed difference (%)	Overall	22 ± 8	15 ± 4	
	Uphill	25 ± 11	17 ± 5	
	Flat	12.1	7.2	
	Downhill	12.5	10.1	
Time loss per lap (seconds)	Overall	21.6	13.9	
	Uphill	19.1	12.2	
	Flat	1.5	0.7	
	Downhill	1.0	0.8	

4.2.2 SUB-TECHNIQUE SELECTION

At lower speed ranges (i.e., 2.75–4.75 m·s^{-1}), the female LW4 skier and female able-bodied skiers selected on average DP, DK, DIA, and OTHER for 61%/43%, 15%/10%, 25%/47%, and 0%/0% of the distance, respectively, while the corresponding numbers for male B3 skiers and male able-bodied skiers were 58%/18%, 1%/13%, 40%/69%, and 1%/0%. At higher speed ranges (i.e., 7–10 m·s^{-1}), the female LW4 skier and female able-bodied skiers selected on average DP and OTHER (i.e., tuck position) for 26%/52% and 74%/48% of the distance, respectively, while the corresponding numbers for male B3 skiers and male able-bodied skiers were 29%/66% and 71%/34% (Figures 23 and 24).

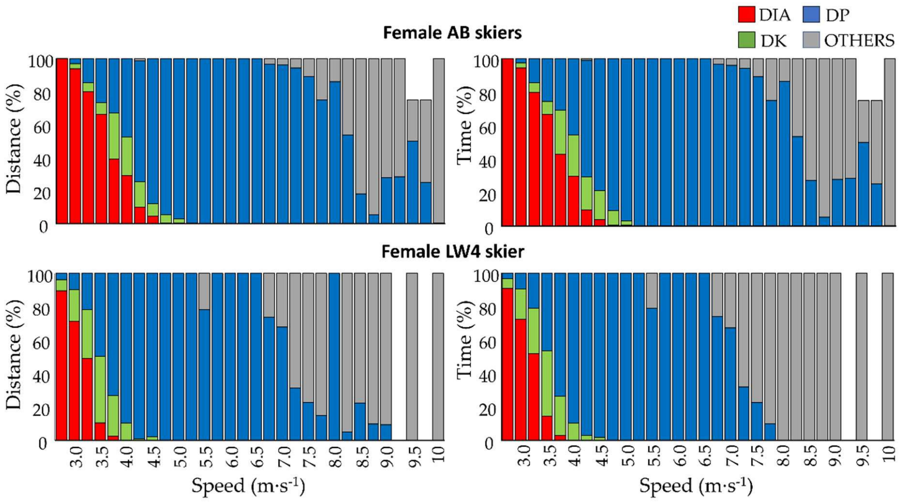


Figure 23. Distribution of sub-techniques over different speed-intervals for the female able-bodied (AB) skiers and the female LW4 skier per distance (left) and per time (right). Diagonal stride (DIA; red); Double poling with kick (DK; green); Double poling (DP; blue); Tuck position and turn technique (OTHER; gray). White sections for able-bodied skiers illustrate that one of the skiers did not use these speeds. White sections for the female LW4 skier illustrate that she did not use these speeds.

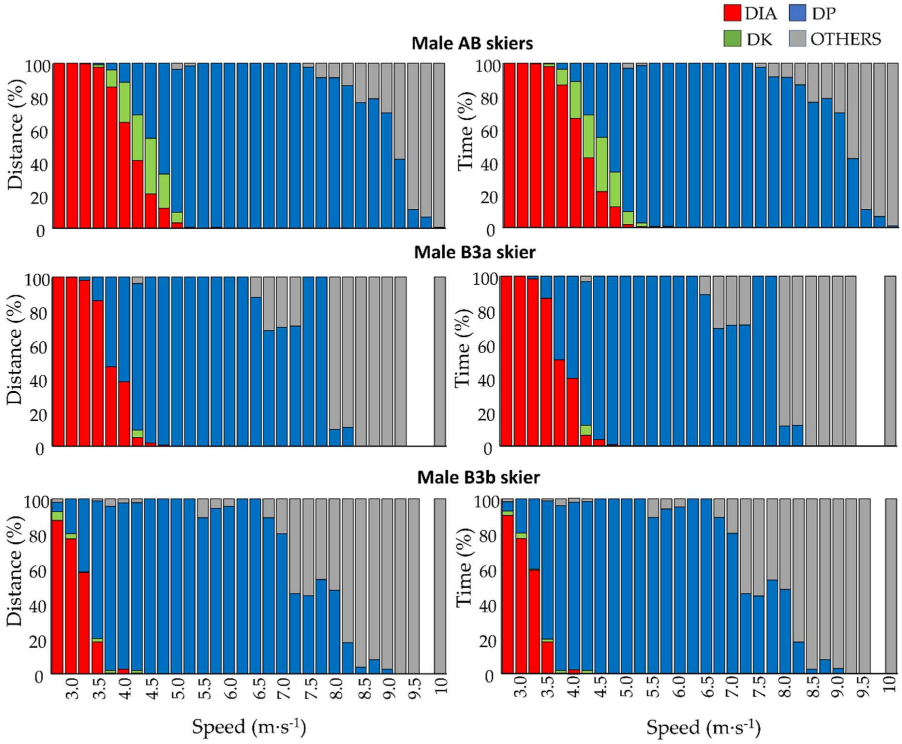


Figure 24. Distribution of sub-techniques over different speed-intervals for the male able-bodied (AB) skiers, the male B3a skier, and the male B3b skier per distance (left) and per time (right). Diagonal stride (DIA; red); Double poling with kick (DK; green); Double poling (DP; blue); Tuck position and turn technique (OTHER; gray); White sections illustrate that the skier did not use these speeds.

4.3 STUDY III

Comparison of Physiological and Biomechanical Responses to Flat and Uphill Cross-Country Sit-Skiing in Able-Bodied Athletes

4.3.1 PHYSIOLOGICAL VARIABLES, RPE, AND WORK RATE

4.3.1.1 Submaximal work rates

Almost all the physiological variables and RPE were higher in FLAT compared with UPHILL (all $p < 0.04$). These variables also displayed an interaction effect between incline and WR and increased yet more when the absolute WR became higher in FLAT compared with UPHILL (all $p < 0.01$) (Figure 25). MR was higher at a given absolute WR in FLAT compared with UPHILL ($p < 0.001$). Additionally, MR displayed an interaction effect between incline and WR, and it increased more when the absolute WR became higher in FLAT compared with UPHILL ($p < 0.001$). GE was higher in UPHILL compared with FLAT ($p < 0.001$). Additionally, GE displayed an interaction effect between incline and WR, and it increased when the absolute WR became higher in UPHILL ($p < 0.001$), but it was stable across the absolute WRs in FLAT ($p = 1.0$) (Figure 25).

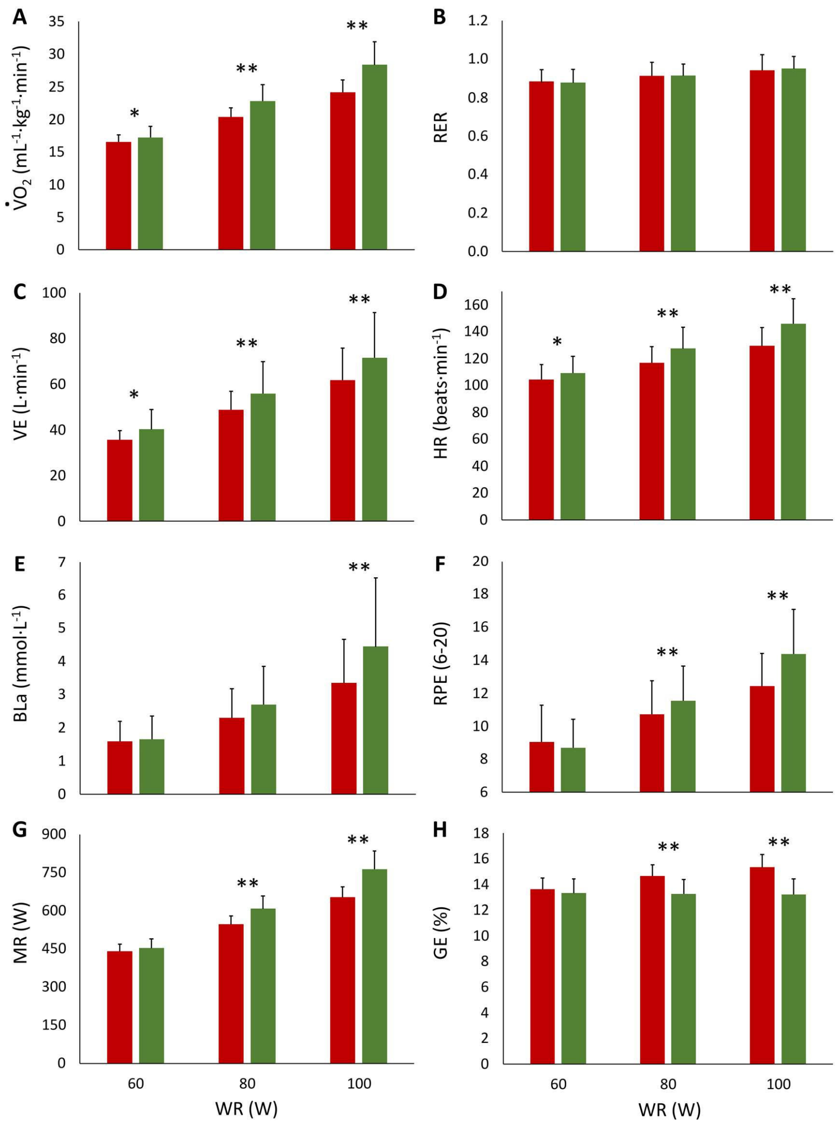


Figure 25. (A) Oxygen uptake ($\dot{V}O_2$), (B) respiratory exchange ratio (RER), (C) minute ventilation (VE), (D) heart rate (HR), (E) blood lactate concentration (BLa), (F) rating of perceived exertion (RPE), (G) metabolic rate (MR), and (H) gross efficiency (GE) presented as mean ± SD at a given absolute work rate (WR) (60, 80, and 100 W) during submaximal upper-body double poling cross-country sit-skiing of 0.5% incline (FLAT; green) and 5% incline (UPHILL; red). *Significant difference between FLAT and UPHILL, $p < 0.05$. **Significant difference between FLAT and UPHILL, $p < 0.01$.

4.3.1.2 *Peak values*

There were no significant differences in the peak physiological variables and RPE between UPHILL and FLAT (all $p > 0.3$) (Figure 26), but a 35% higher WR_{peak} was reached in UPHILL compared with FLAT ($p < 0.001$). The test duration was 147 ± 114 seconds shorter in UPHILL compared with FLAT ($p < 0.001$) (Figure 28).

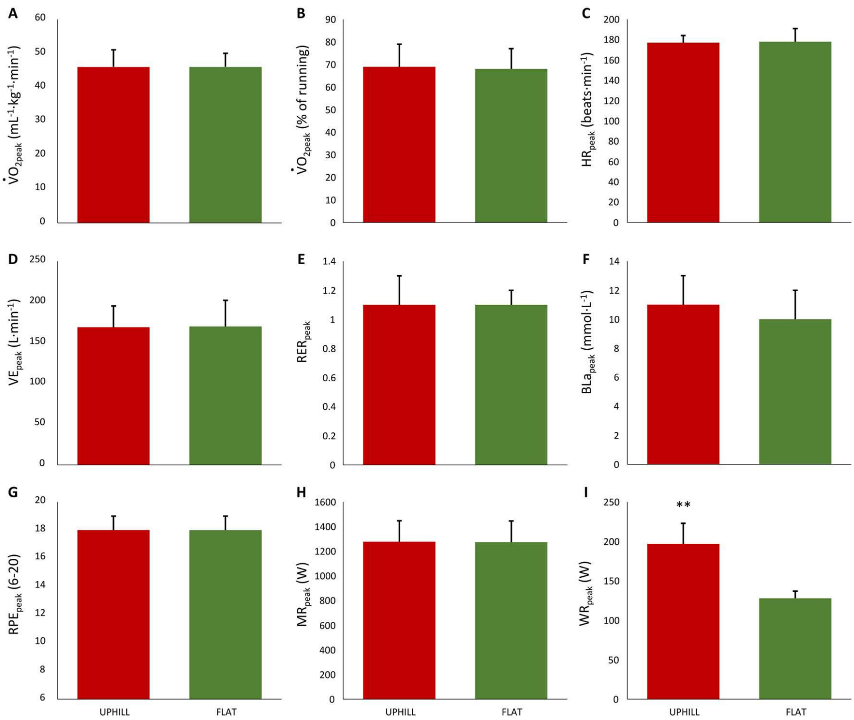


Figure 26. (A) Peak oxygen uptake ($\dot{V}O_{2peak}$), (B) peak oxygen uptake as percent of running ($\dot{V}O_{2peak}$), (C) peak heart rate (HR_{peak}), (D) peak minute ventilation (VE_{peak}), (E) peak respiratory exchange ratio (RER_{peak}), (F) peak blood lactate concentration (BLa_{peak}), (G) peak rating of perceived exertion (RPE_{peak}), (H) peak metabolic rate (MR_{peak}), and peak work rate (WR_{peak}) presented as mean ± SD during maximal upper-body double poling cross-country sit-skiing of 0.5% (FLAT, green) and 5% (UPHILL, red) incline. Note: The highest respiratory values, RPE, and HR reached during either the incremental or the verification test were defined as peak responses (mean ± SD). **Significantly higher in UPHILL compared with FLAT, $p < 0.01$.

4.3.2 CYCLE CHARACTERISTICS

4.3.2.1 *Submaximal work rates*

CL, ST, and relative ST were shorter (all $p < 0.001$) and PT was longer in UPHILL compared with FLAT (all $p < 0.001$). CR, CT, and $work_{cycle}$ did not change between FLAT and UPHILL (all $p > 0.16$), although at 60 W both CR and CT displayed a small difference between FLAT and UPHILL (all $p < 0.05$) (Figure 27). CR, CL, $work_{cycle}$, and relative ST increased when the absolute WR became higher in FLAT and UPHILL (all $p < 0.001$), whereas CT, PT, and relative PT decreased (all $p < 0.001$). ST remained unchanged when the absolute WR became higher in FLAT and UPHILL ($p = 0.14$). CL, ST, relative PT, and relative ST displayed an interaction effect between incline and WR, as CL and relative ST had a larger increase and ST and relative PT had a larger decrease when the absolute WR became higher in FLAT compared with UPHILL (all $p < 0.04$) (Figure 27).

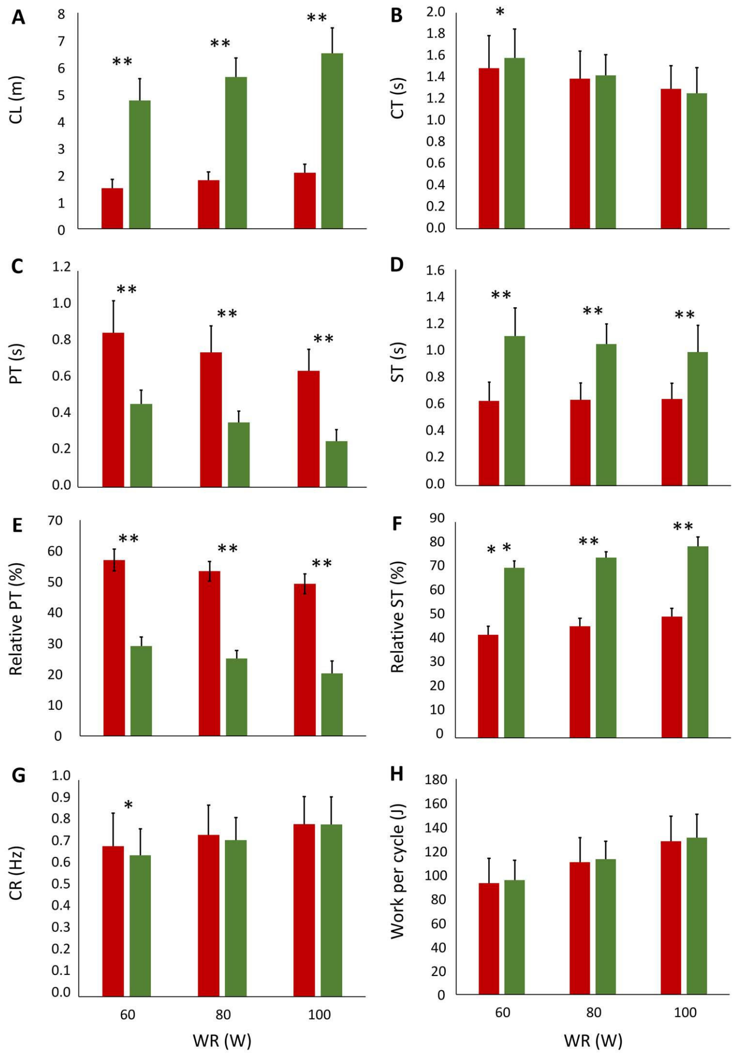


Figure 27. (A) Cycle length (CL), (B) cycle time (CT), (C) poling time (PT), (D) swing time (ST), (E) relative poling time (relative PT), (F) relative swing time (relative ST), (G) cycle rate (CR), and (H) work per cycle presented as mean ± SD at a given absolute work rate (WR) (60, 80, and 100 W) during submaximal upper-body double poling cross-country sit-skiing of 0.5% incline (FLAT; green) and 5% incline (UPHILL; red). *Significant difference between FLAT and UPHILL, $p < 0.05$. **Significant difference between FLAT and UPHILL, $p < 0.01$.

4.3.2.2 *Peak values*

Compared with FLAT, CL was 2.6 ± 0.2 m shorter, PT was 0.14 ± 0.05 s longer, ST was 0.16 ± 0.10 s shorter, relative PT was 17 ± 3 percentage points higher, relative ST was 17 ± 3 percentage points lower, and $work_{cycle}$ was 34 ± 4% higher in UPHILL (all $p < 0.001$) (Figure 28). CT and CR did not display any change between FLAT and UPHILL (all $p > 0.8$) (Figure 28).

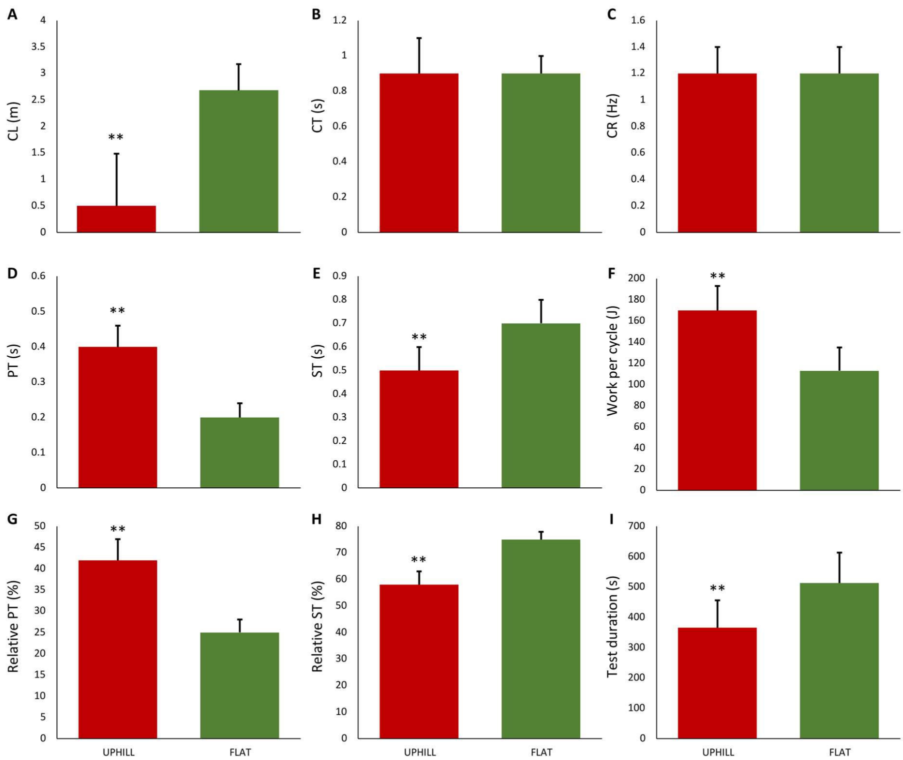


Figure 28. (A) Cycle length (CL), (B) cycle time (CT), (C) cycle rate (CR), (D) poling time (PT), (E) swing time (ST), (F) work per cycle, (G) relative poling time (PT), (H) relative swing time (ST), (I) test duration presented as mean ± SD during maximal upper-body double poling cross-country sit-skiing of 0.5% (FLAT, green) and 5% (UPHILL, red) incline. **Significant difference between UPHILL and FLAT, $p < 0.01$.

4.3.3 PERCEPTUAL AND PHYSIOLOGICAL PARAMETERS IN FLAT AND UPHILL

All perceptual parameters (i.e., RPE_V and RPE_M) and physiological parameters (BLa, $\%HR_{peak}$, and $\%\dot{V}O_{2peak}$), as well as WR, increased as the overall perceived effort (i.e., RPE_T) became higher in FLAT and UPHILL (all $p < 0.01$) (Figures 29 and 30). There was an interaction effect between incline*RPE_T for RPE_V, $\%\dot{V}O_{2peak}$, and WR. While RPE_V was significantly lower in UPHILL compared with FLAT at lower RPE_T (all $p < 0.01$), there were no significant differences at higher RPE_T (all $p > 0.3$) (Figure 29). The $\%\dot{V}O_{2peak}$ was significantly lower in UPHILL compared with FLAT at lower RPE_T (all $p < 0.01$), while there were no significant differences at higher RPE_T (all $p > 0.07$) (Figure 30). WR did not display any significant difference between FLAT and UPHILL at the lowest RPE_T ($p > 0.5$), while WR was significantly higher in UPHILL compared with FLAT at moderate and higher RPE_T (all $p < 0.01$) (Figure 30). When working at a given RPE_T, RPE_V was significantly lower than RPE_M at low, moderate, and high RPE_T in both FLAT and UPHILL (all $p < 0.01$) (Figure 29).

During sit-skiing at a given $RPE_{T,}$ there was an indication of a lower RPE_V and higher RPE_M compared with RPE during able-bodied cross-country skiing at low, moderate, and high RPE_T in both FLAT and UPHILL (Figure 29). At a given RPE_T, BLa reached higher levels after sit-skiing compared able-bodied cross-country skiing at low, moderate, and high RPE_T in both FLAT and UPHILL. During sit-skiing, the skiers seemed to shift from low to moderate RPE_T at lower $\%HR_{peak}$ and $\%\dot{V}O_{2peak}$ compared with skiers during able-bodied cross-country skiing (Figure 30).

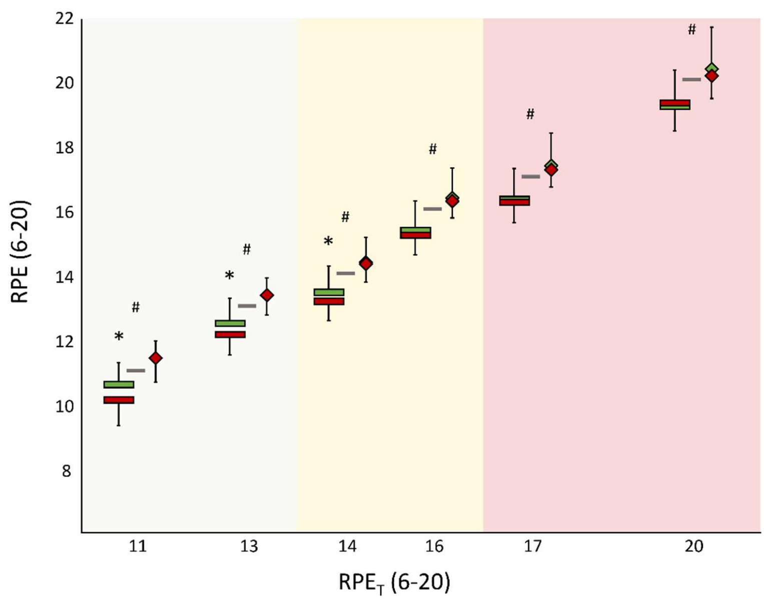


Figure 29. Ventilatory (rectangle) and muscular (diamond) rating of perceived exertion (RPE_V and RPE_M, respectively) recorded during sit-skiing at a given RPE_T in FLAT (dark green) and UPHILL (dark red). The gray lines represent RPE at a given RPE_T during able-bodied cross-country skiing, from which the standardized intensity scale is based on (Figure 7). RPE_T is divided into low (light green), moderate (light yellow), and high (light red) intensity. The rating of perceived exertion (RPE).

Note. The horizontal displacement of the RPE_M and RPE_V is only for the illustration and is connected to the similar RPE_T. * Significant difference between UPHILL and FLAT, $p < 0.04$. # Significantly lower RPE_V than RPE_M, $p < 0.01$.

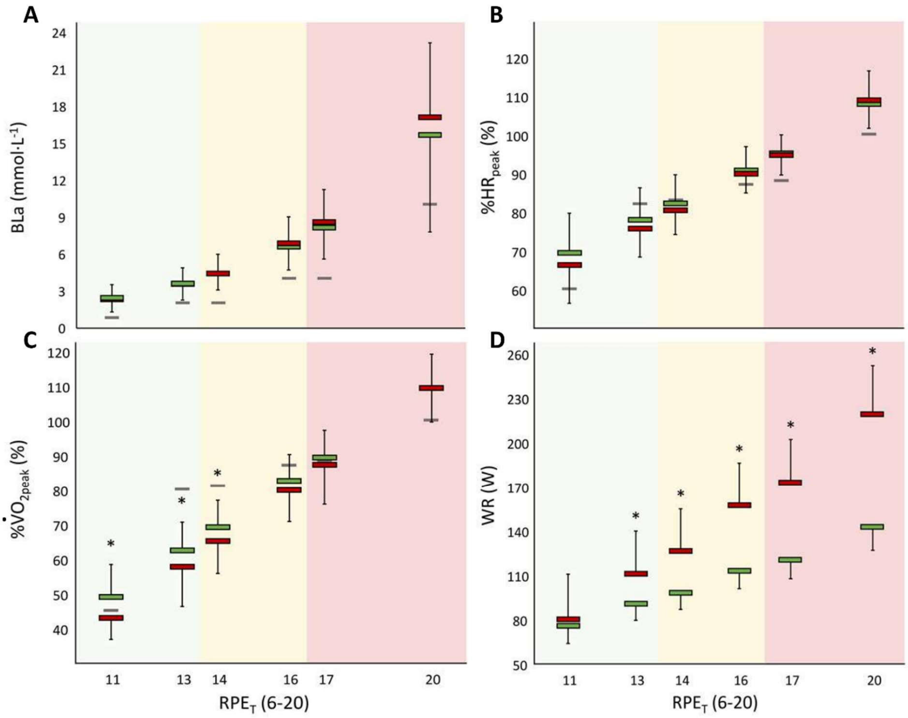


Figure 30. Blood lactate concentration (BLa) (A), percent of peak heart rate (%HR_{peak}) (B), percent of peak oxygen uptake (%$\dot{V}O_{2peak}$) (C), and work rate (WR) (D) obtained during sit-skiing at similar RPE_T in FLAT (dark green) and UPHILL (dark red). The gray lines represent the respective values at a given RPE_T during able-bodied cross-country skiing, from which the standardized intensity scale is based on (Figure 7). RPE_T is divided into low (light green), moderate (light yellow), and high (light red) intensity. The rating of perceived exertion (RPE). * Significant difference between UPHILL and FLAT, $p < 0.01$.

5 DISCUSSION

Overall, the findings presented in this thesis demonstrates that Para skiers display larger RT_{diffs} than able-bodied skiers (Study I). It also demonstrates the feasibility of a framework based on micro-sensor technology to investigate where and why such differences in race times occur during a race (Study II). Furthermore, the thesis shows that higher WR and better efficiency, together with twice as long PT, are achieved when sit-skiing in an uphill condition compared with in a flat condition (Study III).

Firstly, Study I provided novel information about differences in race times, and found that in individual races in World Cups, World Championships, and PWG/OWGs in the 2011–2020 seasons the Para skiers displayed larger RT_{diffs} than able-bodied skiers, and the female skiers displayed larger RT_{diffs} than male skiers. Furthermore, there were no significant differences between RT_{diffs} from the adjusted and unadjusted race times, although the skiers in the Para cross-country skiing categories had a slightly reduced variability in their RT_{diffs} after time factor adjustment (Study I). In the same race data, there was a decrease in the proportion of skiers in the higher classes and an increase in the proportion of skiers in the lower and middle classes for most of the female and male top 3 and top 8 Para skiers after time factor adjustment (additional data).

Secondly, in Study II, the framework based on micro-sensor technology that was used to investigate where and why those differences in race times occurred during a race was evaluated as feasible. For example, with combined high-accuracy positioning and IMU measurements, and validated algorithms, an automatic sub-technique classification accuracy of ~86% and ~96% was reached for the Para skiers with a standing skiing posture (i.e., the LW4 and B3 skiers) and able-bodied skiers, respectively (Study II). Furthermore, in Study II, the descriptive comparison of performance and sub-technique distribution between Para skiers with a standing skiing posture and able-bodied skiers demonstrated that compared with the able-bodied skiers of same sex, the female LW4 skier and male B3 skiers had a 14% and 19% slower average speed, respectively, over the racecourse. Additionally, compared with the able-bodied skiers of the same sex, the female LW4 skier and the male B3 skiers displayed the largest accumulated time loss in uphill terrain, while the relative speed difference between Para skiers with a standing skiing posture and able-bodied skiers were similar in flat and uphill terrain (Study II). Furthermore, the female LW4 skier and the male B3 skiers displayed a different sub-technique distribution than the female and male able-bodied skiers, with a larger proportion of DP than DIA and DK per distance at low speeds (i.e., 2.75–4.75 $m \cdot s^{-1}$) and a larger proportion of tuck than DP per distance at high speeds (i.e., 7–10 $m \cdot s^{-1}$) (Study II).

Thirdly, Study III provided novel information on how performance-determining factors during upper-body double poling cross-country sit-skiing on a treadmill differed between flat and uphill inclines. The skiers utilized longer poling times in uphill sit-skiing, which enabled more work per cycle and better GE, which in turn allowed the skiers to reach a higher WR_{peak} than in flat sit-skiing. Despite a higher WR_{peak} in uphill sit-skiing, the skiers reached a similar $\dot{V}O_{2peak}$ in both the flat and uphill conditions (Study III). Furthermore, when sit-skiing at similar WR, most of the physiological responses were lower, and GE was higher in the uphill condition than in the flat condition (Study III).

5.1.1 RACE DIFFERENCES IN PARA CROSS-COUNTRY SKIING

5.1.1.1 DIFFERENCES IN RACE TIMES ACROSS SKIING GROUPS

The finding of the larger RT_{diffs} for the Para skiers compared with able-bodied skiers (Study I) was in line with previous findings in a study that compared elite Para swimmers and able-bodied swimmers.[153] According to the researchers of that study, the larger RT_{diffs} displayed by the Para swimmers were related to the effect of their disability on their performance, their more limited international race experience, and the slower evolution of the Para sport.[153, 154] Similar factors probably explain the larger RT_{diffs} displayed by the Para skiers compared with their able-bodied counterparts (Study I). Furthermore, in Study I, the Para skiers displayed a larger increase in RT_{diffs} from the top 3 skiers to the top 8 skiers than among the able-bodied skiers (Para: 2.1–6.2%; able-bodied: 0.9–2.1%). This was probably related to a lower number of competitors in Para cross-country skiing than in able-bodied cross-country skiing, which have resulted in a larger proportion of the total number of Para skiers included in the top 8 skiers. Hence, it is likely that the range of performance levels would have been wider for the Para skiers than for the able-bodied skiers, which in turn would have led to increased RT_{diffs} (Study I).

Notably, among the Para cross-country skiing categories, VI skiers displayed larger RT_{diffs} compared with sitting and standing top 8 skiers. This difference was mainly caused by RT_{diffs} of the male Para skiers (Figure 16) (Study I), among whom there was also a larger proportion of skiers in the lower classes compared with the female Para skiers (Figures 18 and 19) (additional data). Additionally, the top 8 male VI skiers include a larger proportion of skiers in lower classes than the male standing and sitting skiers. Since skiers in the lower classes have the most functional limitations, it is likely that the larger RT_{diffs} displayed among the male VI skiers compared with the male standing and sitting skiers was due to larger disability-related performance differences. It can be speculated that also the general level of competitiveness, which is not disability-related, may be reduced among male VI skiers compared with the male sitting and standing skiers. However, this aspect remains to be investigated.

5.1.1.2 DIFFERENCES IN RACE TIMES BETWEEN FEMALE AND MALE SKIERS

The female skiers displayed a larger RT_{diffs} compared with the male skiers, a finding that is in line with previous findings in studies of able-bodied cross-country skiing,[70, 155] skeleton,[156] and slalom kayaking.[157] Particularly, the difference in RT_{diffs} between sexes was mainly due to the able-bodied skiers, while the difference between the sexes of the Para skiers did not reach statistical significance. This was probably due to the small sample sizes and the large variability displayed by the female Para skiers (Study I). Furthermore, the larger RT_{diffs} for female athletes compared with their male counterparts that were demonstrated in able-bodied cross-country skiing,[70, 155] skeleton,[156] and slalom kayaking,[157] were explained by a lower performance levels of the best female athletes compared with the best male athletes.[70, 156] It is probable that this was also the case for the female Para skiers in our study, especially considering that the number of competitors in female races was half that in male races (i.e., on average, in each category there were 24 female skiers vs. 42 male skiers).

5.1.1.3 DIFFERENCES IN RACE TIMES BETWEEN ADJUSTED AND UNADJUSTED RACE TIMES

For the top 3 and top 8 VI, standing, and sitting skiers, the difference between adjusted and unadjusted RT_{diffs} was non-significant, which was probably affected by the large variability in the RT_{diffs}, especially for the unadjusted RT_{diffs}. Even though the change in RT_{diffs} after time factor adjustment was non-significant, it seems that the time factor contributed to less variability in the RT_{diffs} among the Para skiers, especially in the case of the VI skiers (Figures 16 and 17) (Study I). This might have been connected to the distribution of skiers in the higher, middle, and lower classes between the adjusted and unadjusted RT_{diffs} within each Para cross-country skiing category. For several of the female and male Para cross-country skiing categories in the top 3 and top 8 skiers, there were large proportions of skiers in the higher classes for the unadjusted race times (Figures 18 and 19) (additional data). After time factor adjustment, the distribution of classes changed to a smaller proportion of skiers in the higher classes and a larger proportion of skiers in the lower and middle classes. With this change, it is likely that the race times of the skiers in the lower and middle classes would have been incorporated between the race times of the skiers in the higher classes, thus decreasing the variability of the adjusted RT_{diffs}. To date, no study has investigated the distribution of classes before and after time factor adjustment in either Para cross-country skiing or any other Para sport that uses the same classification and time factor system. Overall, these findings indicate that the purpose of the time factor is to reduce disability-related differences between competitors, and that increasing the proportion of skiers in the lower classes after time factor adjustment will give a greater number of skiers an opportunity to win a medal, independent of their disability. Furthermore, the findings serve as baseline for any future studies that will investigate the class distribution in more detail (e.g., including sprint and long-distance races, potential changes over the last ten seasons, and the effect of race distance and skiing technique).

5.1.1.4 DIFFERENCES IN RACE TIMES ACROSS SEASONS

Notably, RT_{diffs} remained relatively stable across the ten seasons (2011–2020) for both the Para skiers and able-bodied skiers (Study I). This finding is in accordance with previous findings in studies of able-bodied cross-country skiing,[70, 155] but for the Para skiers is in contrast to the observation of closer race times in Para sprint running between 1992 and 2012.[158] The relatively stable RT_{diffs} displayed by the Para skiers across the seasons can probably be explained by either an absent performance development during the studied period (i.e., 2011–2020) or a performance development that was equal for all levels of the Para skiers, which left RT_{diffs} unchanged. Even though the differences between adjusted and unadjusted RT_{diffs} were non-significant, a more variable pattern across the ten seasons was displayed by the unadjusted RT_{diffs} compared with the adjusted RT_{diffs}. This indicates that across the last ten seasons the time-factor contributed to less variability in RT_{diffs} among the Para skiers (Study I).

5.2 TERRAIN-SPECIFIC ANALYSES OF RACE PERFORMANCE IN PARA CROSS-COUNTRY SKIING

Differences in race times between competing skiers indicate the performance improvement that is needed to enhance the final ranking or to win the race. Therefore, the findings from Study I are important for skiers and their coaches with regard to the goal setting process and preparation phase, and when evaluating the training progress. In addition to knowledge of how large the differences in race times are, it is even more important to acquire knowledge of where and why a skier increases or decreases the differences in their race times during a race. With continuously changing terrain and external conditions, skiers need to adapt to substantial variation in speed along the track. Therefore, to be able to detect the frequent changes in a skier's performance, tracking both position and time continuously from start to finish would provide detailed information about where and why a skier's performance is changing. By using a case series with Para skiers and able-bodied skiers in Study II, we were able to demonstrate that a framework based on micro-sensor technology was feasible to investigate in-field performance and sub-technique selection continuously during a Para cross-country skiing race.

5.2.1 CONTINUOUS DIFFERENCES IN TIME AND SPEED IN PARA CROSS-COUNTRY SKIING

In accordance with the large speed differences between Para skiers with a standing skiing posture and able-bodied skiers of the same sex, and the proportion of skiing time spent in uphill terrain, also the time loss was largest in this terrain (Study II). Furthermore, the female LW11 sit-skier spent ~50% of her total skiing time in the uphill terrain of the full race course[*] for the sit-skiers, and this finding is in line with previous findings relating to a male LW12 sit-skier[13] and able-bodied cross-country skiers.[18, 19, 36, 61] Additionally, the largest differences in performance between sit-skiers[14, 15] and between able-bodied cross-country skiers[18, 19, 36, 61] have been found in uphill terrain. Notably, the relative speed difference between the Para skiers with a standing skiing posture and able-bodied skiers of the same sex was relatively similar in flat and uphill terrain (Figures 20 and 21) (Study II). The previous studies it has been found that the relative speed differences between able-bodied skiers were smaller in flat terrain compared with in uphill terrain.[18, 36, 61] The large relative speed difference between the Para skiers with a standing skiing posture and able-bodied skiers in flat terrain may be attributed to the reduced balance and motor control of the female LW4 skier[159] and the male B3 skiers,[159, 160] due to their impairments. Since balance and motor control are important qualities of cross-country skiing,[30, 41, 44] any reduction in them might affect the movement pattern for skiing at high speeds on flat terrain. Sitting skiers race on courses with slightly

[*] The entire length of the racecourse for the female LW11 sit-skier is not illustrated in the thesis.

different combinations of terrain (e.g., less steep uphill sections and curved turns) (Table 2) than standing, VI, and able-bodied skiers. In our study (Study II, additional data), the female LW11 sit-skier, the female LW4 skier, and female able-bodied skiers competed on two different racecourses with only two overlapping parts, which limited the possibility to make a direct comparison. However, by using the framework proposed in Study II, it was possible to illustrate clear differences between the female LW11 sit-skier, the female LW4 skier, and the female able-bodied skiers during the two overlapping parts. In the two overlapping parts of the racecourse, a relatively similar amount of the total skiing time was spent in uphill terrain by the female LW11, LW4, and able-bodied skiers (80%, 79%, and 78% of their total skiing time, respectively). Nevertheless, with the lower average speed, the time loss and relative speed differences were larger for the female LW11 sit-skier compared with the female LW4 and female able-bodied skiers in the uphill terrain (additional data). Considering the lack of in-field performance analyses of standing and VI skiers, and that such analyses have been limited to video analysis of specific sections[14] or split-time analysis[15] for sit-skiers, it is recommended that our framework should be used in future large-scale investigations of sitting, standing, and VI skiers' performance during international competitions. This could allow for more in-depth investigations of performance and the effect of terrain and external conditions on the time factor across the Para cross-country skiing classes.

5.2.2 DIFFERENCES IN SUB-TECHNIQUE SELECTION IN PARA CROSS-COUNTRY SKIING

Since sit-skiing is executed using only the upper-body double poling technique, no sub-technique classification of the female LW11 sit-skier was done. However, in study II, the classification of sub-techniques used by the female LW4 and the male B3 skiers during an entire race revealed novel findings of the mechanisms behind Para cross-country skiing performance. When compared with able-bodied skiers, the female LW4 and the male B3 skiers displayed different proportions of the sub-techniques utilized at a given low and high absolute speed. Whereas in a previous study involving a comparison between female and male able-bodied skiers during a classical skiing race, similar proportions in the sub-techniques used at same absolute speeds were found, despite a faster average speed employed by the male able-bodied skiers.[24] The difference between Para skiers with a standing skiing posture and able-bodied skiers with regard to their use of sub-techniques was probably connected to differences in coordinative stability between arms and legs in DP compared with DIA and DK.[161] Since, in our study (Study II), the Para skiers with a standing skiing posture more frequently utilized DP than DIA and DK at low speeds, it could be speculated that DP was less technically demanding and hence more suitable than DIA and DK in the investigated speeds. Additionally, for able-bodied cross-country skiing, it has been suggested that the leg thrust time (i.e., the time during which one ski is in contact with the snow in a leg stride in DIA and DK) has a speed limit that triggers the transition from DIA to DP.[29, 50] Considering the more frequently selected DP found in our study (Study II), such a speed limit might have been present at a lower speed for the Para skiers with a standing skiing posture. Furthermore, the female LW4 and the male B3 skiers more frequently utilized the tuck position than DP at high speeds. Taken together, the above-discussed findings indicate that Para skiers with a standing skiing posture have a choice of sub-techniques that is triggered at different speed thresholds than those suggested for able-bodied skiers.[24, 27, 28, 99] It is probable that the differences are disability-related differences, but further investigation with larger sample sizes is needed. Furthermore, a similar framework as the one presented in Study II has been used in previous studies of able-bodied cross-country skiing, to analyze the kinematic pattern during skiing.[24, 99] Thus, employing the proposed framework (Study II) to investigate the kinematic pattern used by sitting, standing, and VI skiers during an entire skiing race would generate knowledge of speed regulation and the development of race performance. Hence, it is recommended with combined investigations of sub-technique selection and related kinematic patterns used by sitting, standing, and VI skiers in future studies.

5.3 PERFORMANCE-DETERMINANTS OF PARA CROSS-COUNTRY SKIING

The demonstration of the feasibility of the proposed framework for in-field performance analysis of Para cross-country skiing (Study II, additional data) opens up important opportunities for understanding and developing performance during future research on and training of Para skiers. More specifically, in-depth investigations into the effect of terrain and external conditions on the time factor across Para cross-country skiing classes are needed. Furthermore, where and why Para skiers gain or lose time compared with other competitors during a race could be investigated by employing the framework demonstrated in Study II. Even though, it is probable that the physiological and biomechanical performance-determining factors can explain why a skier gains or loses time across different terrain and affects performance, investigation of these factors outdoors is challenging. Performance-determining factors are well studied in able-bodied cross-country skiing (e.g.,[36, 38, 42, 63, 115, 122, 128]), while less is known about them in Para cross-country sit-skiing. Therefore, WR_{peak} and associated performance-determining factors between FLAT (0.5% incline) and UPHILL (5% incline) were compared using upper-body double poling when cross-country sit-skiing on a treadmill (Study III).

5.3.1 PARA CROSS-COUNTRY SKIING IN DIFFERENT TERRAIN

5.3.1.1 SUBMAXIMAL CROSS-COUNTRY SITTING SKIING

When sit-skiing at identical submaximal WRs, the skiers used less physiological effort and their perceptual effort was lower, together with a better GE in the uphill condition compared with in the flat condition (Study III), a finding that is in line with previous findings relating to able-bodied skiers.[31, 72, 144] Furthermore, in the uphill condition, GE increased as the WR became higher. This can probably be attributed to the decreasing impact of the resting metabolic rate, as it constitutes a smaller proportion of the overall metabolic rate when WR increases. However, in the flat condition, GE remained similar, despite an increasing speed and WR, which caused an increased difference in GE between the conditions. Such change in the WR–MR relationship between the flat and uphill condition illustrates that it is more challenging to maintain technique and efficiency when speed increases in a flat condition. Additionally, for the skiers to increase WR with the same amount in both conditions will require a greater MR in the flat condition. Furthermore, in the different conditions, speed was solely regulated through changes in PT and ST, and in the uphill condition the slower speed enabled the skiers to use a longer PT than in the flat condition. Additionally, during the poling phase the muscles were probably working in a more favorable range of the force-velocity relationship and could produce a higher WR.[162] Furthermore, with a shorter ST without any force production, the skiers were also able to generate propulsive forces for a longer time.[31, 35] Together, these probably constitute the main mechanisms behind the better GE in the uphill condition. Despite the lower speed in the uphill condition, the skiers utilized a similar CR in both conditions. This finding is in line with previous findings relating to sit-skiing on snow,[13] but is in contrast to able-bodied cross-country skiing, where a faster CR is utilized as inclines increase.[35] This difference in CR between sitting and able-bodied cross-country skiing is probably related to the range of motion of the trunk, as skiers who are skiing in a standing position can have a greater trunk movement with longer propulsion time that allows them to use CR to regulate speed.

5.3.1.2 MAXIMAL CROSS-COUNTRY SITTING SKIING

Even with different test durations, none of the physiological variables, including $\dot{V}O_{2peak}$, HR_{peak}, and RPE, displayed any differences between the flat and the uphill condition (Study III). Hence, the skiers were able to tax their cardiovascular system similarly, which indicates that the physiological responses are of the same degree in both flat and uphill conditions. These findings are in line with previous findings from a comparison between test durations in seated upper-body poling.[163] Additionally, the authors found a 9% lower WR production when the participants used 140 seconds longer to reach exhaustion.[163] By contrast, the skiers in Study III had a 35% lower WR_{peak} when sit-skiing 147 seconds longer in the flat condition compared with the uphill condition. Thus, it is unlikely that the 35% higher WR_{peak} achieved in the uphill condition can be explained merely by the different test durations. Probably, the difference in WR_{peak} can be attributed to better efficiency working in the uphill condition compared with in the flat condition. Furthermore, the skiers were able to utilize longer PT and achieve a higher $work_{cycle}$ due to the lower speed in the uphill condition compared with in the flat condition. That was related to a higher proportion of the total work production going to overcome gravity in the uphill condition, among other factors.[17, 144] In addition, it can be speculated that the higher WR_{peak} in the uphill condition, as well as the lower physiological variables and RPE at identical submaximal WR, can be connected to a greater force impulse and higher peak pole force later in the cycle, as demonstrated in able-bodied cross-country skiing.[31] However, it remains to be investigated whether or not the same is true in sit-skiing. Nevertheless, in a previous study of sit-skiers,[58] a larger force production was found in the sit-skiers classified as middle and higher (i.e., LW11.5 and LW12) than sit-skiers classified as lower classes (i.e., LW10 and LW11). The larger force production was characterized by greater range of motion in the trunk, smaller pole angles to the ground, and larger force production per cycle.[58] Thus, it is likely that sit-skiers' impairment levels (classification) will have an impact on the force profile displayed in flat and uphill terrain, but this aspect needs further investigation. Furthermore, higher anaerobic contribution in uphill than in flat terrain has been reported in able-bodied cross-country skiing[17, 76] and running.[164] The authors attributed the findings to different muscle fiber recruitment and a greater amount of active muscle mass.[17, 76, 164] In our study (Study III), together with the shorter test duration in the uphill condition, it is possible that an earlier recruitment of fast-twitch muscle-fibers and a higher anaerobic contribution could explain some of the WR_{peak} differences between the uphill and the flat condition. Still, it remains to be investigated whether if sit-skiing in different terrain is accomplished with different amounts of anaerobic energy production, especially in the case of Para skiers in the lower classes with a more limited amount of muscle mass than Para skiers in the higher classes.

5.3.2 PERCEPTUAL AND PHYSIOLOGICAL PARAMETERS FOR INTENSITY REGULATION

During endurance exercise, RPE, $\%HR_{peak}$, and BLa are the parameters most often employed for intensity regulation. When sit-skiing at a given RPE_T, the skiers displayed similar RPE_M, BLa, and $\%HR_{peak}$ in the flat and in the uphill condition, despite a larger WR production (additional data). This finding is in accordance with the lower RPE, BLa, and HR at given absolute WR in the uphill condition compared with in the flat condition (Study III), as well as findings of a higher WR in the uphill condition than in the flat condition at similar metabolic rate and $\%HR_{peak}$ in able-bodied cross-country skiing.[43] Therefore, our findings indicate that the perceptual and physiological parameters connected to the intensity zones can be used interchangeably in flat and uphill terrain.

Despite the lack of data collected regarding perceptual and physiological parameters during able-bodied cross-country skiing, a descriptive comparison of RPE, BLa, $\%HR_{peak}$, and $\%\dot{V}O_{2peak}$ was made between sit-skiing and able-bodied cross-country skiing, on which the standardized intensity scale is based on (Figure 7). At lower, moderate, and higher RPE_T, there was an indication of a lower RPE_V and higher RPE_M during sit-skiing than RPE during able-bodied cross-country skiing in both the flat and the uphill condition. Furthermore, at low, moderate, and high RPE_T, BLa reached higher levels after sit-skiing compared with able-bodied cross-country skiing (additional data). This was probably due to the fact that sit-skiing is performed with a limited amount of active muscle mass with a high production rate of lactate,[139] and a reduced removal from restricted leg muscles, which otherwise with activation would have utilized lactate as energy source.[165, 166] Furthermore, there was a shift from low to moderate RPE_T at lower $\%HR_{peak}$ and $\%\dot{V}O_{2peak}$ during sit-skiing compared with able-bodied cross-country skiing (additional data). Together, the findings indicate an activity-specific variation in the perceptual and physiological parameters between a sitting and standing skiing posture (e.g., between sit-skiing and able-bodied cross-country skiing). Therefore, it is important that sit-skiers and their coaches are aware of these findings if they use the standardized intensity scale employed by able-bodied skiers, as a misleading intensity regulation can cause either a detraining or overtraining effect over time. Probably, it would be advantageous for sit-skiers to individually adapt an intensity scale through systematic use over longer time.

5.3.3 WORK RATE AND SPEED IN PARA CROSS-COUNTRY SKIING

The findings of the performance-determining factors during sit-skiing in Study III in combination with the results of the advanced in-field performance analyses of the Para skiers in Study II have led to an increased understanding of the mechanisms behind why skiers gain or lose time during cross-country skiing races. As implied by the higher WR and better efficiency achieved during sit-skiing in the uphill condition compared with in the flat condition (Study III), the advantages of skiing in uphill terrain allow for a more efficient technical execution of double poling. Hence, a larger amount of the metabolic energy is used to produce WR, and in turn use the body less metabolic energy to increase WR by a given amount in uphill terrain compared with in flat terrain. This finding is in line with previous findings relating to able-bodied cross-country skiing and probably explains why able-bodied skiers find it useful to increase WR above 100% of $\dot{V}O_{2peak}$ in the uphill sections.[17, 18, 63, 64] It is likely that Para skiers will display similar fluctuations as able-bodied skiers in the relationship between the external workload and metabolic energy demand, since we found that the absolute speed of the Para skiers with a standing skiing posture and able-bodied skiers followed a similar pattern when skiing on the same racecourse (Study II). At the same time, there are some indications that skiing in flat terrain caused different physiological and biomechanical responses in the Para skiers with a standing skiing posture than those seen in the able-bodied skiers, which could have influenced the relationship between the external workload and metabolic energy demand. First, the relative speed difference between the Para skiers with a standing skiing posture and able-bodied skiers of the same sex was almost similar in flat and uphill terrain (Study II), where previous studies have found that the relative speed difference between able-bodied skiers is less in flat terrain compared with uphill terrain.[18, 36, 61] Second, when sit-skiing at both submaximal and maximal intensities, the skiers used a similar CR in the flat and uphill conditions[13] (Study III), where able-bodied skiers have been found to display a higher CR when using DP in uphill terrain.[35] These differences between Para and able-bodied skiers are probably attributed to constraints caused by their impairments and/or equipment (and are discussed in more detail above). Nevertheless, fluctuations in the relationship between the external workload and metabolic energy demand across an entire racecourse, still remain to be investigated for both sitting, standing, and VI skiers.

5.4 METHODOLOGICAL CONSIDERATIONS

When interpreting the findings of Study I, II, and III, some limitations should be taken into account. In Study I, the calculations of RT_{diffs} were done in a slightly different way than in other studies that have investigated differences in race times (e.g., able-bodied cross-country skiing[70] and Para swimming[153]). In Study I, percentage RT_{diffs} were directly calculated from the absolute race times before the analyses, whereas the mentioned studies[70, 153] log-transformed the race times prior to the analyses to get the variability and differences as percentages of the mean when back-transformed. Therefore, caution is needed if our results are directly compared with findings from other studies. Additionally, for Study I, the unadjusted race times were calculated for all ten seasons using the time factor that was employed in the 2019–2020 season. Even though the time factor is evaluated every season by the IPC,[7] and minor changes might have been made during the studied period (i.e., 2011–2020), it is unlikely that the results of the comparisons between the adjusted and unadjusted RT_{diffs} were affected. For Study II, the proposed framework was applied to one LW4 skier, two B3 skiers, and one LW11 sit-skier who were competing on the presented racecourse/sections of the racecourse and external condition. The algorithm used for automatic sub-technique classification for the Para skiers was constructed for able-bodied skiers. Considering the Para skiers' different impairments might have affected their movement pattern related to the sub-techniques, the accuracy of the automatic sub-technique classification for the Para skiers could have been reduced compared with the able-bodied skiers. Therefore, the algorithm should in future studies be adapted to all sitting and standing Para cross-country skiing categories and validated in larger populations. Additionally, different external conditions (e.g., low-speed vs. high-speed racecourses, with and without trees or other obstacles along the course, and weather conditions) can have an influence on the accuracy of the GNSS receiver. Since only one type of external condition was examined in Study II, skiers and their coaches need to take this limitation into consideration when using the framework in training and/or competition under different external conditions. Therefore, in future studies, the framework's feasibility should be tested under different external conditions. In Study III, able-bodied skiers were chosen with the purpose of reducing the high within-group differences of the maximal aerobic capacity and WR previously found in Para sit-skiers with different impairments.[125, 149] Additionally, sit-skiing was performed using one sitting position ("kneeing") by all skiers. Hence, caution is warranted if the findings are directly generalized to Para sit-skiers with different disabilities and sitting positions (Figure 2), as both the disability[167, 168] and sitting position[131-133] can affect the physiological performance-determining factors. Therefore, future studies should investigate the generalizability of the findings of Study III to Para sit-skiers. However, our findings still serve as a baseline for future research that includes Para skiers.

5.5 PRACTICAL APPLICATIONS

The novel findings from the three studies and supplementary analyses provide knowledge for Para skiers and their coaches, both for evaluating and developing Para cross-country skiing performance (for a summary of the applications, see Figure 31).

The RT_{diffs} displayed by the Para skiers (Study I) indicate the performance improvement needed to gain a better rank or to win a race. This information can be used by skiers and their coaches when new goals are defined, and training progress is evaluated. Furthermore, the framework evaluated in Study II would be highly useful to obtain detailed information on where and why a Para skier gains or loses time compared with his or her competitors during a race. If the time and speed data are combined with sub-technique analyses, they could provide details about which sub-techniques the Para skier utilizes at different speeds, in different terrains, and in different external conditions, as well as how the skier regulates their speed within each sub-technique. Additionally, if the framework were to be used in studies of larger groups of Para skiers, it could provide a detailed understanding of how the differences in speed between categories, classes, and sexes are influenced by sub-technique and terrain. Therefore, the findings could help Para skiers either individually or on a group level to construct targeted training and competition strategies. As an example from Study II, compared with the able-bodied skiers, the female LW4 and the male B3 skiers displayed, along with a large relative speed difference in flat terrain, a different distribution of the classical sub-techniques at high skiing speeds. Thus, it seems that the movement pattern is differently exposed to the high skiing speeds of Para skiers with a standing skiing posture and able-bodied skiers. Such information can be used by the skiers and their coaches to decide what kind of training individual skiers should prioritize (e.g., whether to improve balance and technique execution at high skiing speed or to increase aerobic capacity to develop performance in uphill terrain). Furthermore, the testing approach employed in Study III created a highly useful tool to investigate in detail the physiological and biomechanical aspects behind skiers' performance in different inclines and speeds. Such information can help both skiers and coaches to construct individual targeted training strategies and to evaluate performance progress over time. To evaluate training progress, $\dot{V}O_{2peak}$ is an often-tested determinant of endurance athletes.[47, 116, 117, 128, 129] In Study III, the skiers reached similar $\dot{V}O_{2peak}$ sit-skiing in the flat and the uphill condition, which indicated a similar level of stimulation of the physiological responses. Therefore, $\dot{V}O_{2peak}$ testing can be performed in both a flat and uphill conditions. Additionally, training for improving $\dot{V}O_{2peak}$ can probably be done in both flat and uphill terrain, despite a much lower WR production in flat terrain. Alternatively, if the intention is to evaluate development of GE during a training period, the external conditions must be standardized, as both incline and WR affect GE (in Study III, GE was better in the uphill condition than in the flat condition, with an increasing difference with higher WR). Furthermore, for skiers, it is important to balance training intensity over time in order to achieve performance-enhancing adaptations and still avoid overtraining.[169] To accomplish this, skiers and their coaches must plan, execute, and evaluate the training. The perceptual and physiological parameters used for intensity regulation reached similar values for almost all parameters when sit-skiing at a given RPE_T in the flat condition and the uphill condition (additional data). Hence, the findings indicate that the perceptual and physiological parameters connected to the intensity zones can be used interchangeably in flat and uphill terrain.

Even though the testing approach in Study III was executed on able-bodied skiers' upper-body double poling sit-skiing, a similar approach would probably be suitable for both sitting, standing, and VI skiers too.

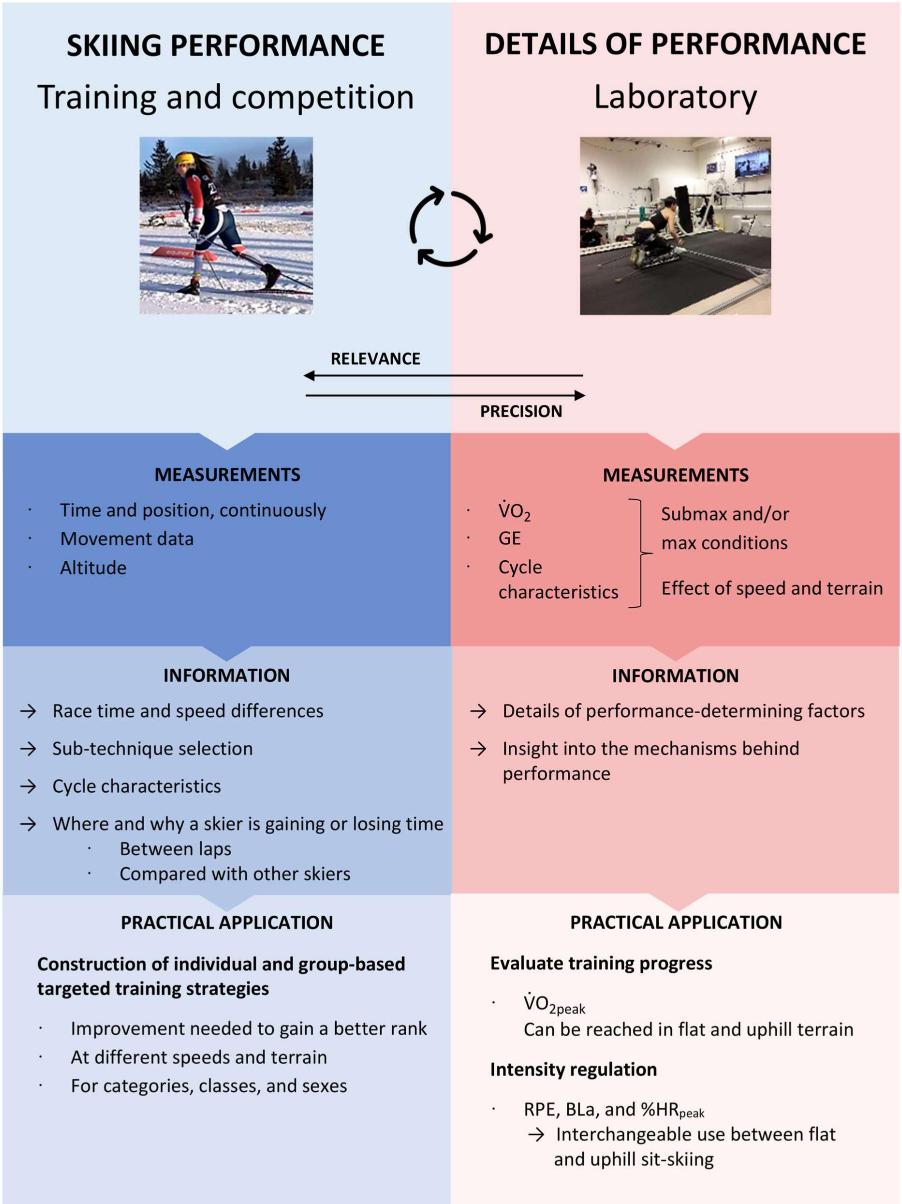


Figure 31. Overview of the practical applications for Para skiers and their coaches provided by Study I, II, and III, and the supplementary analyses.
Blood lactate concentration (BLa); Gross efficiency (GE); Lactate threshold (LT); Oxygen uptake ($\dot{V}O_2$); Peak oxygen uptake ($\dot{V}O_{2peak}$); Percent of peak heart rate ($\%HR_{peak}$); Rating of perceived exertion (RPE).

6 CONCLUSIONS

Overall, this thesis demonstrates that there are larger RT_{diffs} among Para skiers than among able-bodied skiers (Study I). It also demonstrates the feasibility of a framework based on micro-sensor technology to investigate where and why the aforementioned differences in race times occur during a race (Study II). Furthermore, it shows that a higher WR and better efficiency can be achieved in uphill terrain compared with in flat terrain while sit-skiing, which may explain why skiers distribute more energy and why performance difference are largest in uphill terrain during a race (Study III).

Compared with the able-bodied skiers, the Para skiers in Study I displayed larger RT_{diffs}, which probably can be attributed to disability-related differences in performance and fewer Para skiers. Furthermore, larger RT_{diffs} were displayed by the female skiers than by their male counterparts, but the statistical significance was mainly caused by the able-bodied skiers. It is probable that this was related to a small number of female Para skiers with large variability in the RT_{diffs}. Furthermore, adjusted and unadjusted RT_{diffs} did not differ significantly. Still, adjusted RT_{diffs} were less variable, which probably can be attributed the effect of the time factor on the race times (Study I). After time factor adjustment, there was a decrease in the proportion of skiers in the higher classes and an increase in the proportion of skiers in the lower and middle classes for most of the female and male Para skiers. Such changes indicate the purpose of the time factor is to reduce the disability-related performance difference between skiers (additional data). In addition to knowledge of how large differences in race times are, it is even more important to obtain knowledge of where and why a skier increases or decreases the differences in race times during a race. In the descriptive comparison of performance and sub-technique selection between Para skiers with a standing skiing posture and able-bodied skiers that was done in Study II, the Para skiers revealed that the largest time loss was in the uphill terrain. Furthermore, the relative speed difference between Para skiers with a standing skiing posture and able-bodied skiers was similar in flat and uphill terrain, which differs from the results of other studies showing a lower relative speed difference in flat terrain than uphill terrain between sexes or performance levels within able-bodied skiers. The finding can probably be attributed to a disability-related effect on the technical execution of skiing at high speeds on flat terrain. Furthermore, given that the female LW4 and the male B3 skiers more frequently selected DP than DIA and DK at low speeds and tuck position than DP at high speeds, it could be speculated that DP is more suitable at low speeds and more frequently selected tuck position at high speeds, due to lower coordinative demands. This indicates that, compared with able-bodied skiers, the Para skiers with a standing skiing posture have other speed thresholds for the classical sub-techniques and are likely to be affected by the Para skiers' impairments. Furthermore, the proposed framework was evaluated as feasible because with high-accuracy positioning measurements and IMU measurements, and validated algorithms, it had an automatic sub-technique classification accuracy of ~86% and ~96% for the Para skiers with a standing skiing posture and able-bodied skiers, respectively. Thus, it is recommended that the framework should be used in future large-scale investigations of skiing performance. More specifically, the framework makes it possible to investigate how the terrain and external conditions affect the time factor across the Para cross-country skiing classes. Furthermore, the investigations of the physiological and biomechanical performance-determining factors in Study III demonstrated that a higher WR_{peak} was achieved during sit-skiing in uphill compared with in a flat incline on a treadmill. The higher WR_{peak} was enabled through longer poling times that allowed more work per cycle and better GE than flat sit-skiing. These findings indicate the advantages of lower speed when sit-skiing uphill at both submaximal and maximal intensities, allowing a more efficient technique with a larger proportion of the metabolic energy going to produce work. Considering that most time is spent in uphill terrain during a cross-country skiing race, skiers can gain more time using less metabolic energy if they increase their effort in uphill terrain compared with in flat and downhill terrain, due to the more efficient technique used in uphill terrain. However, the skiers still reached similar $\dot{V}O_{2peak}$ values in both conditions, indicating that the skiers had the ability to tax their cardiorespiratory system to the same level (Study III). Furthermore, during sit-skiing at a given RPE_T, the RPE_M, BLa, and $\%HR_{peak}$ were similar between conditions at low, moderate, and high RPE_T, despite a higher WR in the uphill condition than the flat condition (additional data). Hence, these findings indicate that the perceptual and physiological parameters associated with the intensity zones can be used interchangeably between flat and uphill terrain.

7 REFERENCES

1. Jahnke B. *Paralympic Winter Games 1976-2006, Örnsköldsvik - Torino*. International Paralympic Committee; 2006.
2. Vanlandewijck YC, Thompson WR. *The Paralympic Athlete: Handbook of Sports Medicine and Science*. Wiley-Blackwell; 2011.
3. Gold JR, Gold MM. Access for all: the rise of the Paralympic Games. *J R Soc Promot Health*. 2007; 127(3):133-41. doi:10.1177/1466424007077348
4. IPC. History of Para Nordic Skiing. Accessed May 27, 2022. https://www.paralympic.org/nordic-skiing/about
5. Tweedy SM, Vanlandewijck YC. International Paralympic Committee position stand-background and scientific principles of classification in Paralympic sport. *Br J Sports Med*. 2011; 45(4):259-69. doi:10.1136/bjsm.2009.065060
6. Legg D, Steadward R. The Paralympic Games and 60 years of change (1948–2008): unification and restructuring from a disability and medical model to sport-based competition. *Sport in Society*. 2011; 14(9):1099-1115. doi:https://doi.org/10.1080/17430437.2011.614767
7. IPC. What is classification? World Para Nordic Skiing. Accessed May 27, 2022. https://www.paralympic.org/classification
8. Rosso V, Gastaldi L. Towards Beijing 2022: Discussion on the growth in size of Paralympic Winter Games in terms of participating data from Örnsköldvik 1976 to PyeongChang 2018. *J Hum Sport Exerc*. 2020; doi:10.14198/jhse.2021.164.13
9. Stalin S, Creese M, Dalton KN. Visual function of visually impaired Paralympic skiers. *Frontiers in Neuroscience*. 2021; 15(648648) doi:https://doi.org/10.3389/fnins.2021.648648
10. IPC. World Para Nordic Skiing Homologation Guide. Accessed June 11, 2022, https://www.paralympic.org/sites/default/files/document/171116152536727_World+Para+Nordic+Skiing+Homologation+Guide2017_0.pdf
11. IPC. The International Paralympic Committee, World Para Snow Sports. Accessed May 27, 2022. https://www.paralympic.org/nordic-skiing/about
12. FIS. Cross-Country Homologation Manual. Accessed June 11, 2022, https://assets.fis-ski.com/image/upload/v1540977224/fis-prod/FIS_homologation_manual_2018_jaa_v3.pdf
13. Baumgart JK, Haugnes P, Bardal LM, Østerås S, Kocbach J, Sandbakk Ø. Development of a framework for the investigation of speed, power, and kinematic patterns in Para cross-country sit-skiing: a case study of an LW12 athlete. *Front Sports Act Living*. 2019; doi:https://doi.org/10.3389/fspor.2019.00004
14. Bernardi M, Janssen T, Bortolan L, Pellegrini B, Fischer G, Schena F. Kinematics of cross-country sit skiing during a Paralympic race. *J Electromyogr Kinesiol*. 2012; 23(1):94-101. doi:10.1016/j.jelekin.2012.07.004
15. Karczewska-Lindinger M, Gastaldi L, Vanlandewijc Y, Linnamo V, Lindinger S. Race and split time analysis in Para Nordic sit-skiing. Presented at: 8th International Congress on Science and Skiing; 2019; University of Jyväskylä, Vuokatti, Finland.
16. Andersson EA, Lundahl G, Wecke L, Lindblom I, Nilsson J. Maximal aerobic power versus performance in two aerobic endurance tests among young and old adults. *Gerontology*. 2011; 57(6):502-12. doi:10.1159/000329174
17. Karlsson Ø, Gilgien M, Gløersen ØN, Rud B, Losnegard T. Exercise intensity during cross-country skiing described by oxygen demands in flat and uphill terrain. *Front Physiol*. 2018; 9:846. doi:10.3389/fphys.2018.00846
18. Sandbakk Ø, Ettema G, Leirdal S, Jakobsen V, Holmberg HC. Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur J Appl Physiol*. 2011; 111(6):947-57. doi:10.1007/s00421-010-1719-9

19. Andersson E, Supej M, Sandbakk Ø, Sperlich B, Stöggl T, Holmberg HC. Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur J Appl Physiol*. 2010; 110(3):585-95. doi:10.1007/s00421-010-1535-2
20. Brodersen J, Schwartz LM, Heneghan C, O'Sullivan JW, Aronson JK, Woloshin S. Overdiagnosis: what it is and what it isn't. *BMJ Evidence-Based Medicine*. 2018; 23:1-3.
21. Losnegard T. Energy system contribution during competitive cross-country skiing. *Eur J Appl Physiol*. 2019; doi:10.1007/s00421-019-04158-x
22. Solli GS, Kocbach J, Seeberg TM, et al. Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *PLoS One*. 2018; 13(11):1-21. doi:10.1371/journal.pone.0207195
23. Welde B, Stöggl TL, Mathisen GE, et al. The pacing strategy and technique of male cross-country skiers with different levels of performance during a 15-km classical race. *PLoS One*. 2017; 12(11) (e0187111):1-18. doi:10.1371/journal.pone.0187111
24. Solli GS, Kocbach J, Sandbakk SB, 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):1-17. doi:https://doi.org/10.1371/journal.pone.0239862
25. 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. doi:10.3389/fphys.2017.00094
26. Ettema G, Kveli E, Øksnes M, Sandbakk Ø. The role of speed and incline in the spontaneous choice of technique in classical roller-skiing. *Hum Mov Sci*. 2017; 55:100-107.
27. Marsland F, Anson J, Waddington G, Holmberg HC, Chapman DW. Macro-kinematic differences between sprint and distance cross-country skiing competitions using the classical technique. *Front Physiol*. 2018; 9:1-8. doi:10.3389/fphys.2018.00570
28. Marsland F, Mackintosh C, Holmberg HC, et al. Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition. *PLoS One*. 2017; 12(8):1-15. doi:10.1371/journal.pone.0182262
29. Pellegrini B, Zoppirolli C, Bortolan L, Holmberg HC, Zamparo P, Schena F. Biomechanical and energetic determinants of technique selection in classical cross-country skiing. *Hum Mov Sci*. 2013; 32(6):1415-29. doi:10.1016/j.humov.2013.07.010
30. 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(5):807-18.
31. Stöggl T, Holmberg HC. Double-poling biomechanics of elite cross-country skiers: flat versus uphill terrain. *Med Sci Sports Exerc*. 2016; 48(8):1580-9. doi:10.1249/mss.0000000000000943
32. Göpfert C, Holmberg HC, Stöggl T, Müller E, Lindinger SJ. Biomechanical characteristics and speed adaptation during kick double poling on roller skis in elite cross-country skiers. *Sports Biomech*. 2013; 12(2):154-74. doi:10.1080/14763141.2012.749939
33. Hébert-Losier K, Zinner C, Platt S, Stöggl T, Holmberg HC. Factors that Influence the Performance of Elite Sprint Cross-Country Skiers. *Sports Med*. 2017; 47(2):319-342. doi:10.1007/s40279-016-0573-2
34. Bucher Sandbakk S, Supej M, Sandbakk Ø, Holmberg HC. Downhill turn techniques and associated physical characteristics in cross-country skiers. *Scand J Med Sci Sports*. 2014; 24(4):708-16. doi:10.1111/sms.12063
35. 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:10.1371/journal.pone.0212500
36. 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. doi:10.3389/fphys.2016.00326

37. Sollie O, Gløersen Ø, Gilgien M, Losnegard T. Differences in pacing pattern and sub-technique selection between young and adult competitive cross-country skiers. *Scand J Med Sci Sports*. 2021; 31(3):553-563. doi:10.1111/sms.13887

38. Stöggl T, Pellegrini B, Holmberg HC. Pacing and predictors of performance during cross-country skiing races: A systematic review. *J Sport Health Sci*. 2018; 7(4):381-393. doi:10.1016/j.jshs.2018.09.005

39. Ohtonen O. Biomechanics in cross-country skiing skating technique and measurement techniques of force production. *JYU dissertations*. 2019;

40. Hoffman MD, Clifford PS, Bender F. Effect of velocity on cycle rate and length for three roller skiing techniques. *Journal of Applied Biomechanics*. 1995; 11(3):257-266.

41. Lindinger SJ, Stöggl T, Müller 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. doi:10.1249/MSS.0b013e318184f436

42. 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):473-81. doi:10.1007/s00421-010-1372-3

43. Sandbakk Ø, Ettema G, Holmberg HC. The influence of incline and speed on work rate, gross efficiency and kinematics of roller ski skating. *Eur J Appl Physiol*. 2012; 112(8):2829-2838.

44. Stöggl T, Müller E, Ainegren M, Holmberg HC. General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand J Med Sci Sports*. 2011; 21(6):791-803.

45. Bilodeau B, Rundell KW, Roy B, Boulay MR. Kinematics of cross-country ski racing. / Cinematiques des competitions de ski de fond. *Medicine & Science in sports & exercise*. 1996; 28(1):128-138.

46. Stöggl T, Lindinger S, Müller E. Analysis of a simulated sprint competition in classical cross-country skiing. *Scand J Med Sci Sports*. 2007; 17(4):362-72. doi:10.1111/j.1600-0838.2006.00589.x

47. Sandbakk Ø, Holmberg HC. Physiological capacity and training routines of elite cross-country skiers: approaching the upper limits of human endurance. *Int J Sports Physiol Perform*. 2017; 12(8):1003-1011. doi:10.1123/ijspp.2016-0749

48. Andersson E, Pellegrini B, Sandbakk Ø, Stöggl T, Holmberg HC. The effects of skiing velocity on mechanical aspects of diagonal cross-country skiing. *Sports Biomech*. 2014a; 13(3):267-84. doi:10.1080/14763141.2014.921236

49. Andersson E, Stöggl T, Pellegrini B, Sandbakk Ø, Ettema G, Holmberg HC. Biomechanical analysis of the herringbone technique as employed by elite cross-country skiers. *Scand J Med Sci Sports*. 2014b; 24(3):542-552.

50. Nilsson J, Tveit P, Eikrehagen O. Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomech*. 2004; 3(1):85-107.

51. Ohtonen O, Linnamo V, Lindinger SJ. Speed control of the V2 skating technique in elite cross-country skiers. *International Journal of Sports Science & Coaching*. 2016; 11(2):219-230.

52. Stöggl T, Welde B, Supej M, et al. Impact of incline, sex and level of performance on kinematics during a distance race in classical cross-country skiing. *J Sports Sci Med*. 2018; 17(1):124-133.

53. Boulay MR, Rundell KW, King DL. Effect of slope variation and skating technique on velocity in cross-country skiing. *Med Sci Sports Exerc*. 1995; 27(2):281-7.

54. Lindinger SJ, 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):353-63. doi:10.1007/s00421-009-1018-5

55. Lindinger SJ, Göpfert C, Stöggl T, Müller E, Holmberg HC. Biomechanical pole and leg characteristics during uphill diagonal roller skiing. *Sports Biomech*. 2009; 8(4):318-33. doi:10.1080/14763140903414417

56. 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. doi:10.1249/mss.0000000000000723

57. Stöggl T, Müller E, Ainegren M, Holmberg HC. General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand J Med Sci Sports*. 2011; 21(6):791-803. doi:10.1111/j.1600-0838.2009.01078.x
58. Karczewska-Lindinger M, Linnamo V, Rosso V, et al. Force generation profiles of Para-nordic sit-skiers representing different physical impairments. *J of Sci in Sport and Exercise*. 2021; doi:https://doi.org/10.1007/s42978-021-00117-1
59. Abbiss CR, Laursen PB. Describing and understanding pacing strategies during athletic competition. *Sports Med*. 2008; 38(3):239-52. doi:10.2165/00007256-200838030-00004
60. Losnegard T, Kjeldsen K, Skattebo Ø. An analysis of the pacing strategies adopted by elite cross-country skiers. *J Strength Cond Res*. 2016; 30(11):3256-3260. doi:10.1519/jsc.0000000000001424
61. 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):873-80. doi:10.1123/ijspp.2014-0335
62. Formenti D, Rossi A, Calogiuri G, Thomassen TO, Scurati R, Weydahl A. Exercise intensity and pacing strategy of cross-country skiers during a 10 km skating simulated race. *Res Sports Med*. 2015; 23(2):126-39. doi:10.1080/15438627.2015.1005298
63. Andersson E, Björklund G, Holmberg HC, Ørtenblad N. Energy system contributions and determinants of performance in sprint cross-country skiing. *Scand J Med Sci Sports*. 2017; 27(4):385-398. doi:10.1111/sms.12666
64. Andersson E, Govus A, Shannon OM, McGawley K. Sex differences in performance and pacing strategies during sprint skiing. *Front Physiol*. 2019; 10:295. doi:10.3389/fphys.2019.00295
65. Gløersen Ø, Gilgien M, Dysthe DK, Malthe-Sørenssen A, Losnegard T. Oxygen demand, uptake, and deficits in elite cross-country skiers during a 15-km Race. *Med Sci Sports Exerc*. 2020; 52(4):983-992. doi:10.1249/mss.0000000000002209
66. Welde B, Evertsen F, Von Heimburg E, Medbø IJ. Energy cost of free technique and classical cross-country skiing at racing speeds. *Med Sci Sports Exerc*. 2003; 35(5):818-25.
67. Sandbakk Ø. Let's close the gap between research and practice to discover new land together! *Int J Sports Physiol Perform*. 2018; 13(961) (8) doi:https://doi.org/10.1123/ijspp.2018-0550
68. Bishop D. An applied research model for the sport sciences. *Sports Med*. 2008; 38(3):253-63. doi:10.2165/00007256-200838030-00005
69. Bishop D, Burnett A, Farrow D, Gabbett T, Newton R. Sports-science roundtable: does sports-science research influence practice? *Int J Sports Physiol Perform*. 2006; 1(2):161-8. doi:10.1123/ijspp.1.2.161
70. Spencer M, Losnegard T, Hallen J, Hopkins WG. Variability and predictability of performance times of elite cross-country skiers. *Int J Sports Physiol Perform*. 2014; 9(1):5-11. doi:10.1123/ijspp.2012-0382
71. Forbes SC, Chilibeck PD, Craven B, Bhambhani Y. Comparison of a double poling ergometer and field test for elite cross country sit skiers. *N Am J Sports Phys Ther*. 2010; 5(2):40-6.
72. Sandbakk Ø, Hegge AM, Ettema G. The role of incline, performance level, and gender on the gross mechanical efficiency of roller ski skating. *Front Physiol*. 2013; 4:293. doi:10.3389/fphys.2013.00293
73. Sandbakk Ø, Skalvik TF, Spencer M, et al. The physiological responses to repeated upper-body sprint exercise in highly trained athletes. *Eur J Appl Physiol*. 2015; 115(6):1381-91. doi:10.1007/s00421-015-3128-6
74. 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*. 2019:1190-1199. doi:10.1123/ijspp.2018-0471
75. Carlsen CH, Rud B, Myklebust H, Losnegard T. Pole lengths influence O(2)-cost during double poling in highly trained cross-country skiers. *Eur J Appl Physiol*. 2018; 118(2):271-281. doi:10.1007/s00421-017-3767-x

76. Andersson E, Holmberg HC, Ørtenblad N, Björklund G. Metabolic responses and pacing strategies during successive sprint skiing time trials. *Med Sci Sports Exerc*. 2016; 48(12):2544-2554. doi:10.1249/mss.0000000000001037
77. Haugnes P, Torvik P, Ettema G, Kocbach J, Sandbakk Ø. 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):788–795. doi:10.1123/ijspp.2018-0507
78. Seeberg TM, Tjønnås J, Rindal OMH, Haugnes P, Dalgard S, Sandbakk Ø. A multi-sensor system for automatic analysis of classical cross-country skiing techniques. *Sports Eng*. 2017; 20:313-327. doi:10.1007/s12283-017-0252-z
79. Muthukrishnan K. *Multimodal Localisation: Analysis, Algorithms and Experimental Evaluation.* Ph.D. University of Twente; 2009.
80. Swarèn M, Stöggl T, Supej M, Eriksson A. Usage and validation of a tracking system to monitor position and velocity during cross-country skiing. *International Journal of Performance Analysis in Sport*. 2016; 16:769-785.
81. Zory R, Vuillerme N, Pellegrini B, Schena F, Rouard A. Effect of fatigue on double pole kinematics in sprint cross-country skiing. *Hum Mov Sci*. Feb 2009; 28(1):85-98. doi:10.1016/j.humov.2008.05.002
82. Sathyan T, Shuttleworth R, Hedley M, K. D. Validity and reliability of a radio positioning system for tracking athletes in indoor and outdoor team sports. *Behav Res Methods*. 2012; 44(4):1108-14. doi:10.3758/s13428-012-0192-2
83. 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. doi:10.3389/fphys.2018.01425
84. Supej M, Cuk I. Comparison of global navigation satellite system devices on speed tracking in road transport applications. *Sensors (Basel)*. 2014; 14(12):23490-23508. doi:10.3390/s141223490
85. Marsland F, Mackintosh C, Anson J, Lyons K, Waddington G, Chapman DW. Using micro-sensor data to quantify macro kinematics of classical cross-country skiing during on-snow training. *Sports Biomech*. 2015; 14(4):435-47. doi:10.1080/14763141.2015.1084033
86. Lindinger SJ, Holmberg HC. How do elite cross-country skiers adapt to different double poling frequencies at low to high speeds? *Eur J Appl Physiol*. 2011; 111(6):1103-19. doi:10.1007/s00421-010-1736-8
87. 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):1225-1233.
88. Stöggl T, Holst A, Jonasson A, et al. Automatic classification of the sub-techniques (gears) used in cross-country ski skating employing a mobile phone. *Sensors (Basel)*. 2014; 14(11):20589-601. doi:10.3390/s141120589
89. Nilsson J, Tinmark F, Halvorsen K, Arndt A. Kinematic, kinetic and electromyographic adaptation to speed and resistance in double poling cross-country skiing. *Eur J Appl Physiol*. 2013; 113(6):1385-94. doi:10.1007/s00421-012-2568-5
90. Stöggl T, Holmberg HC. Force interaction and 3D pole movement in double poling. *Scand J Med Sci Sports*. 2011; 21(6):e393-404. doi:10.1111/j.1600-0838.2011.01324.x
91. Grasaas E, Hegge A, Ettema G, Sandbakk Ø. The effects of poling on physiological, kinematic and kinetic responses in roller ski skating. *Eur J Appl Physiol*. 2014; 114(9):1933-42. doi:10.1007/s00421-014-2926-6
92. Stöggl T, Holmberg HC. Three-dimensional force and kinematic interactions in V1 skating at high speeds. *Med Sci Sports Exerc*. 2015; 47(6):1232-42. doi:10.1249/MSS.0000000000000510
93. Millet GY, Hoffman MD, Candau RB, Buckwalter JB, Clifford PS. Cycle rate variations in roller ski skating: effects on oxygen uptake and poling forces. *Int J Sports Med*. 1998; 19(8):521-525.

94. Marsland F, Lyons K, Anson J, Waddington G, Macintosh C, Chapman D. Identification of cross-country skiing movement patterns using micro-sensors. *Sensors (Basel)*. 2012; 12(4):5047-66. doi:10.3390/s120405047
95. Marsland F, Mackintosh C, Holmberg HC, et al. Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition. *PLoS One*. 2017; 12(8):e0182262. doi:10.1371/journal.pone.0182262
96. Rindal OMH, Seeberg TM, Tjønnas J, Haugnes P, Sandbakk Ø. Automatic classification of sub-techniques in classical cross-country skiing using a machine learning algorithm on micro-sensor data. *Sensors (Basel)*. 2017; 18(1) doi:10.3390/s18010075
97. Sakurai Y, Fujita Z, Ishige Y. Automated identification and evaluation of subtechniques in classical-style roller skiing. *J Sports Sci Med*. 2014; 13(3):651-7.
98. Sakurai Y, Fujita Z, Ishige Y. Automatic identification of subtechniques in skating-style roller skiing using inertial sensors. *Sensors (Basel)*. 2016; 16(4) doi:10.3390/s16040473
99. Solli GS, Kocbach J, Seeberg TM, et al. Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *PLoS One*. 2018; 13(11):e0207195. doi:10.1371/journal.pone.0207195
100. Myklebust H, Losnegard T, Hallén J. Differences in V1 and V2 ski skating techniques described by accelerometers. *Scand J Med Sci Sports*. 2014; 24(6):882-93. doi:10.1111/sms.12106
101. Solli GS, 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(e0239862) (9) doi:10.1371/journal.pone.0239862
102. Myklebust H. *Quantification of movement patterns in cross-country skiing using inertial measurement units*. 2016.
103. Ohtonen O, Linnamo V, Lindinger S. Effects of gliding properties of cross-country skis on the force production during skating technique in elite cross-country skiers. *International Journal of Sports Science & Coaching*. 2013; 8(2)
104. Kavanagh JJ, Menz HB. Accelerometry: a technique for quantifying movement patterns during walking. *Gait Posture*. 2008; 28(1):1-15. doi:doi:10.1016/j.gaitpost.2007.10.010
105. Aminian K, Najafi B. Capturing human motion using body-fixed sensors: outdoor measurement and clinical applications. *Comp Anim Virtual Worlds*. 2004; 15:79-94. doi:10.1002/cav.2
106. Myklebust H, Gløersen Ø, Hallén J. Validity of ski skating center-of-mass displacement measured by a single inertial measurement unit. *J Appl Biomech*. 2015; 31(6):492-8. doi:10.1123/jab.2015-0081
107. Losnegard T, Myklebust H, Ehrhardt A, Hallén J. Kinematical analysis of the V2 ski skating technique: A longitudinal study. *J Sports Sci*. 2017; 35(12):1219-1227.
108. Gastaldi L, Mauro S, Pastorelli S. Analysis of the pushing phase in Paralympic cross-country sit-skiers - Class LW10. *J Adv Res*. 2016; 7(6):971-978. doi:10.1016/j.jare.2016.10.003
109. Gastaldi L, Pastorelli S, Frassinelli S. A biomechanical approach to Paralympic cross-country sit-ski racing. *Clin J Sport Med*. 2012; 22(1):58-64. doi:10.1097/JSM.0b013e31824202d3
110. Karczewska-Lindinger M, Gastaldi L, Vanlandewijc Y, Linnamo V, Lindinger S. Race and split time analysis in para nordic sit-skiing. Presented at: 8th International Congress on Science and Skiing (ICSS); 2019; Vuokatti, Finland.
111. Rosso V, Gastaldi L, Rapp W, Lindinger S, Vanlandewijck Y, Linnamo V. Biomechanics of simulated versus natural cross-country sit skiing. *J Electromyogr Kinesiol*. 2017; 32:15-21. doi:10.1016/j.jelekin.2016.11.002
112. Rosso V, Linnamo V, Rapp W, et al. Simulated skiing as a measurement tool for performance in cross-country sit-skiing. *J Sports Engineering and Technology*. 2019; 233(4):455-466. doi:10.1177/1754337119843415
113. Karczwska-Lindinger M, Linnamo V, Rosso V, et al. Class-specific biomechanical characteristics of double poling in elite Paralympic Nordic sit-skiers. Presented at: 7th International Congress on Science and Skiing (ICSS); 2016; St. Christoph/Arlberg - Austria.

114. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol*. 2008; 586(1):35-44. doi:10.1113/jphysiol.2007.143834
115. Ainegren M, Carlsson P, Tinnsten M, Laaksonen MS. Skiing economy and efficiency in recreational and elite cross-country skiers. *J Strength Cond Res*. 2013; 27(5):1239-52. doi:10.1519/JSC.0b013e31824f206c
116. Holmberg HC. The elite cross-country skier provides unique insights into human exercise physiology. *Scand J Med Sci Sports*. 2015; 25 Suppl 4:100-9. doi:10.1111/sms.12601
117. 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 Sports*. 2007; 17(4):437-44. doi:10.1111/j.1600-0838.2006.00592.x
118. Losnegard T, Hallén J. Elite cross-country skiers do not reach their running VO2max during roller ski skating. *J Sports Med Phys Fitness*. 2014; 54(4):389-93.
119. Losnegard T, Schäfer D, Hallén J. Exercise economy in skiing and running. *Front Physiol*. 2014; 5:5. doi:10.3389/fphys.2014.00005
120. Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc*. 2000; 32(1):70-84.
121. Saltin B, Strange S. Maximal oxygen uptake: "old" and "new" arguments for a cardiovascular limitation. *Med Sci Sports Exerc*. 1992; 24(1):30-7.
122. Losnegard T, Myklebust H, Hallen J. Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc*. 2012; 44(4):673-81. doi:10.1249/MSS.0b013e3182388684
123. Bernardi M, Guerra E, Di Giacinto B, Di Cesare A, Castellano V, Bhambhani Y. Field evaluation of Paralympic athletes in selected sports: implications for training. *Med Sci Sports Exerc*. Jun 2010; 42(6):1200-8. doi:10.1249/MSS.0b013e3181c67d82
124. Bernardi M, Carucci S, Faiola F, et al. Physical fitness evaluation of Paralympic winter sports sitting athletes. *Clin J Sport Med*. 2012; 22(1):26-30. doi:10.1097/JSM.0b013e31824237b5
125. Baumgart JK, Brurok B, Sandbakk Ø. Peak oxygen uptake in Paralympic sitting sports: A systematic literature review, meta- and pooled-data analysis. *PLoS One*. 2018; 13(2):e0192903. doi:10.1371/journal.pone.0192903
126. Ingjer F. Maximal oxygen uptake as a predictor of performance ability in women and men elite cross-country skiers. *Scan Journal of Medicine & Science in Sports*. 1991; 1(1):25-30. doi:https://doi.org/10.1111/j.1600-0838.1991.tb00267.x
127. Saltin B, Åstrand PO. Maximal oxygen uptake in athletes. *J Appl Physiol*. 1967; 23(3):353-8. doi:10.1152/jappl.1967.23.3.353
128. 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. doi:10.1249/mss.0000000000000862
129. Tønnessen E, Haugen TA, Hem E, Leirstein S, Seiler S. Maximal aerobic capacity in the winter-Olympics endurance disciplines: Olympic-medal benchmarks for the time period 1990-2013. *Int J Sports Physiol Perform*. 2015; 10(7):835-9. doi:10.1123/ijspp.2014-0431
130. Bhambhani Y, Forbes S, Forbes J, Craven B, Matsuura C, Rodgers C. Physiologic responses of competitive Canadian cross-country skiers with disabilities. *Clin J Sport Med*. 2012; 22(1):31-8. doi:10.1097/JSM.0b013e3182432f0c
131. Hofmann KB, Ohlsson ML, Höök M, Danvind J, Kersting UG. The influence of sitting posture on mechanics and metabolic energy requirements during sit-skiing: a case report. *Sports Eng*. 2016; 19(3):213-218.
132. Lajunen K, Rapp W, Ahtiainen JP, Lindinger SJ, Linnamo V. Effect of sitting posture on sit-skiing economy in non-disabled athletes. *Front Sports Act Living*. 2020; 2:44. doi:10.3389/fspor.2020.00044
133. Ohlsson ML, Laaksonen MS. Sitting position affects performance in cross-country sit-skiing. *Eur J Appl Physiol*. 2017; 117(6):1095-1106. doi:10.1007/s00421-017-3596-y
134. Seiler S, Tønnessen E. Intervals, thresholds, and long slow distance: the role of intensity and duration in endurance training. *Sportscience*. 2009; 13:32-53. doi:sportsci.org/2009/ss.htm

135. Seiler KS, Kjerland G. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? *Scand J Med Sci Sports*. 2006; 16(1):49-56. doi:10.1111/j.1600-0838.2004.00418.x
136. Borg GA. Perceived exertion: a note on "history" and methods. *Med Sci Sports*. 1973; 5(2):90-3.
137. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982; 14(5):377-81.
138. Scherr J, Wolfarth B, Christle JW, Pressler A, Wagenpfeil S, Halle M. Associations between Borg's rating of perceived exertion and physiological measures of exercise intensity. *Eur J Appl Physiol*. 2013; 113(1):147-55. doi:10.1007/s00421-012-2421-x
139. Beneke R, Leithäuser RM, Hütler M. Dependence of the maximal lactate steady state on the motor pattern of exercise. *Br J Sports Med*. 2001; 35(3):192-6. doi:10.1136/bjsm.35.3.192
140. Beneke R, von Duvillard SP. Determination of maximal lactate steady state response in selected sports events. *Med Sci Sports Exerc*. 1996; 28(2):241-6. doi:10.1097/00005768-199602000-00013
141. Hoffman MD, Clifford PS, Foley PJ, Brice AG. Physiological responses to different roller skiing techniques. *Med Sci Sports Exerc*. 1990; 22(3):391-6.
142. Larson AJ. Variations in heart rate at blood lactate threshold due to exercise mode in elite cross-country skiers. *J Strength Cond Res*. 2006; 20(4):855-60. doi:10.1519/r-16424.1
143. Olympiatoppen. OLT I-SKALA. Accessed March 15, 2022. https://olt-skala.nif.no/I-skala_2020.pdf
144. Sandbakk Ø, Ettema G, Holmberg HC. The influence of incline and speed on work rate, gross efficiency and kinematics of roller ski skating. *Eur J Appl Physiol*. 2012; 112(8):2829-38. doi:10.1007/s00421-011-2261-0
145. Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G. The physiology of world-class sprint skiers. *Scand J Med Sci Sports*. 2011; 21(6):e9-16. doi:10.1111/j.1600-0838.2010.01117.x
146. Stöggl TL, Müller E. Kinematic determinants and physiological response of cross-country skiing at maximal speed. *Medicine & Science in sports & exercise*. 2009; 41(7):1476-1487.
147. IPC. International Paralympic Committee. Accessed May 27, 2022. https://www.paralympic.org/
148. FIS. The International Ski Federation. Calender and results. Accessed May 27, 2022. https://www.fis-ski.com/DB/cross-country/calendar-results.html?noselection=true
149. Janssen TW, Dallmeijer AJ, Veeger DJ, van der Woude LH. Normative values and determinants of physical capacity in individuals with spinal cord injury. *J Rehabil Res Dev*. 2002; 39(1):29-39.
150. Leicht CA, Tolfrey K, Lenton JP, Bishop NC, Goosey-Tolfrey VL. The verification phase and reliability of physiological parameters in peak testing of elite wheelchair athletes. *Eur J Appl Physiol*. 2013; 113(2):337-45. doi:10.1007/s00421-012-2441-6
151. Lusk G. Animal calorimetry: twenty-fourth paper. Analysis of the oxidation of mixtures of carbohydrate and fat. *J Biol Chem*. 1924; 59::41-42.
152. Ettema G, Loras HW. Efficiency in cycling: a review. *Eur J Appl Physiol*. 2009; 106(1):1-14. doi:10.1007/s00421-009-1008-7
153. Fulton SK, Pyne D, Hopkins WG, Burkett B. Variability and progression in competitive performance of Paralympic swimmers. *J Sports Sci*. 2009; 27(5):535-9. doi:10.1080/02640410802641418
154. Daly DJ, Vanlandewijck YC. Some criteria for evaluating the ‘‘fairness’’ of swimming classification. *Adapt Phys Activ Q*. 1999; 16:271-289.
155. Stöggl T, Stöggl J, Müller E. Competition analysis of the last decade (1996 – 2008) in cross-country skiing. In: Müller E, Stöggl T, eds. *Science and Skiing IV*. Meyar & Meyar Sport; 2009.
156. Bullock N, Hopkins WG, Martin DT, Marino FE. Characteristics of performance in skeleton World Cup races. *J Sports Sci*. 2009; 27(4):367-72. doi:10.1080/02640410802613425

157. Nibali M, Hopkins WG, Drinkwater E. Variability and predictability of elite competitive slalom canoe-kayak performance. *Eur J Sport Sci*. 2011; 11(2):125-130. doi:0.1080/17461391.2010.487121
158. Grobler L, Ferreira S, Terblanche E. Paralympic sprint performance between 1992 and 2012. *Int J Sports Physiol Perform*. 2015; 10(8):1052-4. doi:10.1123/ijspp.2014-0560
159. Norges Skiforbund. Accessed May 27, 2022. https://www.skiforbundet.no/langrenn
160. Klavina A, Jekabsone I. Static balance of persons with intellectual disabilities, visual impairments and without disabilities. *EUJAPA*. 2014; 7(1):50-57.
161. Cignetti F, Schena F, Zanone PG, Rouard A. Dynamics of coordination in cross-country skiing. *Hum Mov Sci*. 2009; 28(2):204-17. doi:10.1016/j.humov.2008.11.002
162. Hill AV. The maximum work and mechanical efficiency of human muscles, and their most economical speed. *J Physiol*. 1922;
163. Brurok B, Mellema M, Sandbakk Ø, Baumgart JK. Effects of different increments in workload and duration on peak physiological responses during seated upper-body poling. *Eur J Appl Physiol*. 2019; 119(9):2025-2031. doi:10.1007/s00421-019-04189-4
164. Olesen HL. Accumulated oxygen deficit increases with inclination of uphill running. *J Appl Physiol (1985)*. 1992; 73(3):1130-4. doi:10.1152/jappl.1992.73.3.1130
165. Secher NH, Clausen JP, Klausen K, Noer I, Trap-Jensen J. Central and regional circulatory effects of adding arm exercise to leg exercise. *Acta Physiol Scand*. 1977; 100(3):288-97. doi:10.1111/j.1748-1716.1977.tb05952.x
166. Van Hall G, Jensen-Urstad M, Rosdahl H, Holmberg HC, Saltin B, Calbet JA. Leg and arm lactate and substrate kinetics during exercise. *Am J Physiol Endocrinol Metab*. 2003; 284(1):E193-205. doi:10.1152/ajpendo.00273.2002
167. Berlowitz DJ, Wadsworth B, Ross J. Respiratory problems and management in people with spinal cord injury. *Breathe (Sheff)*. 2016; 12(4):328-340. doi:10.1183/20734735.012616
168. Theisen D. Cardiovascular determinants of exercise capacity in the Paralympic athlete with spinal cord injury. *Exp Physiol*. 2012; 97(3):319-24. doi:10.1113/expphysiol.2011.063016
169. Faulkner JA. New perspectives in training for maximum performance. *Jama*. 1968; 205(11):741-6.
170. Millet G, Hoffman M, Candau R, Clifford P. Poling forces during roller skiing: effects of grade. *Medicine & Science in sports & exercise*. 1998;
171. Stöggl TL, Holmberg HC. Double-poling biomechanics of elite cross-country skiers: flat versus uphill terrain. *Med Sci Sports Exerc*. 2016; 48(8):1580-9. doi:10.1249/mss.0000000000000943
172. Stöggl T, Lindinger S, Müller E. Analysis of a simulated sprint competition in classical cross-country skiing. *Scand J Med Sci Sports*. 2007; 17(4):362-372.
173. Losnegard T, Myklebust H, Hallén J. No differences in O2-cost between V1 and V2 skating techniques during treadmill roller skiing at moderate to steep inclines. *J Strength Cond Res*. 2012; 26(5):1340-7. doi:10.1519/JSC.0b013e318231a69e
174. Larsson P, Henriksson-Larsen K. Combined metabolic gas analyser and dGPS analysis of performance in cross-country skiing. *J Sports Sci*. 2005; 23(8):861-70. doi:10.1080/02640410400022078
175. Takeda M, Miyamoto N, Endo T, et al. Cross-country skiing analysis and ski technique detection by high-precision kinematic global navigation satellite system. *Sensors (Basel)*. 2019; 19(22) doi:10.3390/s19224947

APPENDIX

Appendix 1. Overview of the effect of the kinematic patterns during different conditions in the classical and freestyle skiing techniques for able-bodied skiers. The aim of the table is to give an indication of the complex interaction between speed, terrain, sub-technique, and the related kinematic pattern.

Condition	Parameter	Effect	Sub-technique: Classical	Sub-technique: Freestyle
Increasing speed	CL	**Increase ↑**		
		· Uphill	DIA [22, 48, 50] DK [22, 32] HRB [22, 49]	V1 [92] V2 [42, 43, 51, 146]
		· Flat	DK [22, 40, 50] DP [40, 41]	V1 [40, 50, 170] V2 [43, 50]
		· Downhill	DK [22]	V2a [50] Leg skate [50]
		Decrease ↓		
		· Uphill	DP [22]	
		· Flat	DP [22, 46]	
		· Downhill	DP [22]	
		Steady →		
		· Flat	DP [146, 170, 171]	
		· Uphill	DIA [46, 146] DP [171]	
	CR	**Increase ↑**		
		· Uphill	DIA [46, 48, 146] DK [22] DP [22, 171] HRB [49]	V1 [92] V2 [42, 43, 51, 146]
		· Flat	DIA [22, 50] DK [22, 40, 50] DP [22, 40, 41, 46, 50, 146, 170, 171]	V1 [40, 50, 170] V2 [43, 50]
		· Downhill	DIA [22] DK [22] DP [22]	V2a [50] Leg skate [50]
	PT_{abs}	**Decrease ↓**		
		· Uphill	DIA [48, 146] DK [32] DP [35, 171] HRB [49]	V1 [92] V2 [43, 146]
		· Flat	DP [146, 170, 171]	V2 [43]
		Steady →		
		· Flat	DP [41]	

	PT_{rel}	**Decrease**		
		· Uphill	DP [35]	V2 [43, 51]
			DKP [32]	
		· Flat	DP [41]	
		Steady		
		· Uphill	HRB [49]	V2 [146]
			DIA [146]	
		· Flat	DP [146]	
Maximal speed	**CL**	**Plateau**		
		· Uphill	HRB [49]	V2 [51]
		· Flat	DP [41]	V1 [170]
		Decrease		
		· Uphill	DIA [48, 146]	V2 [92, 146]
		· Flat	DIA [50]	V1 [40, 50]
			DK [40, 50]	V2 [50]
			DP [40, 50, 146, 170]	V2a [50]
				Leg skate [50]
	PT_{abs}	**Plateau**		
		· Flat	DP [41]	
	PT_{rel}	**Plateau**		
		· Flat	DP [41]	
Increasing incline	**CL**	**Decrease**		
		· 0°-11°	DIA [23, 52]	
			DK [23, 52]	
		· -1%-12%	DIA [23, 52]	V1 [53]
				V2 [53]
				V2a [53]
	CR	**J-shaped increase**		
		· 0°-11°	DIA [52]	
			DK [52]	
			DP [52]	
Uphill compared with flat/less inclined uphill	**CL**	**Decrease**		
		· PO_{uphill} > PO_{flat}	DP [171]	
		· Similar MR		V2 [43]
	CR	**Increase**		
		· PO_{uphill} > PO_{flat}	DP [171]	
		· Similar speed	DP [35]	
		· Similar MR		V2 [43]
	PT_{abs}	**Increase**		
		· PO_{uphill} > PO_{flat}	DP [171]	
		· Similar speed	DP [35]	
		· Similar MR		V2 [43]
	PT_{rel}	**Increase**		

		· $PO_{uphill} > PO_{flat}$	DP [171]	
		· Similar speed	DP [35]	
		· Similar MR		V2 [43]
	ST_{abs}	**Decrease** ↓		
		· $PO_{uphill} > PO_{flat}$	DP [171]	
	ST_{rel}	**Decrease** ↓		
		· $PO_{uphill} > PO_{flat}$	DP [171]	
Correlations	CL_{submax} and V_{max}	**Positive** +		
		· Flat	DP [146, 172]	
		· Uphill	DIA [146, 172]	V2 [51, 146]
		No correlation ✖		
		· Uphill		V1 [92]
	CL_{submax} and V_{submax}	**Positive** +		
		· Uphill		V1 [53]
				V2 [53]
				V2a [53]
		· Flat		V1 [53]
				V2 [53]
				V2a [53]
		· Downhill		V1 [53]
				V2 [53]
				V2a [53]
	CL_{max} and V_{max}	**Positive** +		
		· Uphill	DIA [172]	
		· Flat	DP [172]	
	CL and $Speed_{average}$	**Positive** +		
		· Uphill	DIA [23, 45]	V1 [45]
			DK [23]	V2a [45]
			DP [23, 45]	
		· Flat	DIA [23]	
			DK [23]	
			DP [23]	
		No correlation ✖		
		· Flat	DIA [45]	V1 [45]
			DP [45]	V2a [45]
	CL and Performance	**Negative** −		
	· Longer	· Uphill		V1 [173]
				V2 [173]
	$CR_{submaximal}$ and V_{max}	**Negative** −		
		· Uphill	DIA [146, 172]	V2 [146]
		· Flat	DP [146, 172]	

	No correlation ✖		
	· Uphill		V1 [53]
			V2 [53]
			V2a [53]
$CR_{submaximal}$ and $V_{submaximal}$	· Flat		V1 [53]
			V2 [53]
			V2a [53]
	· Downhill		V1 [53]
			V2 [53]
			V2a [53]
	No correlation ✖		
	· Uphill	DIA [23, 45]	V1 [45]
		DK [23]	V2a [45]
CR and $Speed_{average}$		DP [23, 45]	
	· Flat	DIA [23, 45]	
		DK [23]	
		DP [23, 45]	
	No correlation ✖		
CR_{max} and V_{max}	· Uphill	DIA [172]	
	· Flat	DP [172]	
CR and Performance	**Negative** ➖		
· Unchanged	· Uphill		V1 [173]
· Higher			V2 [173]
	Positive ✚		
CL and $PT_{abs, rel}$	· Uphill		V2 [43]
	· Flat		V2 [43]

Absolute poling time (PT_{abs}); Average skiing speed ($Speed_{average}$); Cycle length (CL); Cycle length at maximal speed (CL_{max}); Cycle length at submaximal speed (CL_{submax}); Cycle rate (CR); Diagonal stride (DIA); Double dance (V2); Double poling (DP); Double poling with kick (DK); Herringbone (HRB); Maximal velocity (V_{max}); Metabolic rate (MR); Padling (V1); Power output flat (PO_{flat}); Power output uphill (PO_{uphill}); Relative poling time (PT_{rel}); Relative swing time (ST_{rel}); Single dance (V2a); Submaximal velocity (V_{submax}); Steady (➔); Increase (↑); Decrease (↓); Increase with plateau (↗); J-shaped increase (↷): Positive correlation (✚); Negative correlation (➖); No correlation (✖).

Appendix 2. Overview of a selection of research done of Para cross-country sit-skiing (marked yellow) and able-bodied cross-country skiing that have employed different technological devices for position and movement tracking.

Technology	Receiver	Reference system	Parameter	Modality	Accuracy / Advantages	Research	Limitations
POSITION TRACKING							
GNSS	1 Hz wrist-worn GPS receiver (Garmin forerunner)		Position Time Speed Course profile	In-field XC skiing race (10 and 15 km)	Practical and easy to use Low interference with the skier	[36, 61]	Reduced accuracy of the position data compared with differential GNSS
				In-field XC skiing, low and high intensity training		[78, 99]	
	10 Hz differential GPS (d-GPS)		Position Speed Time	In-field XC skiing simulation, 5.6 km freestyle	The correlation coefficient between speed of a chronometry and speed of a d-GPS: ~0.9995	[174]	1100 g equipment on head and body
	d-GNSS system (receiver and antenna)		Position Time Speed -> External PO	In-field roller-skiing, high intensity	Accuracy < 5 cm Use both GLONASS and GPS satellites	[17]	940 g equipment on head and body
	10 Hz kinematic GNSS (external antenna on the head)	50 Hz video camera	Position Time Speed Distance	In-field simulated XC skiing race, 5.3 km classical time-trail	98.6 % match between GNSS and video recording Higher precision of speed and time, than single point GNSS or d-GPS Accuracy: 5.66 cm on average Ability to connect technique distribution with position, altitude, and horizontal velocity on a full course Light sensor, 69 g	[175]	Only one participant

	1 Hz wrist-worn receiver (Gar-920XT) 10 Hz standalone receiver (Cat-S5) 10 Hz d-GNSS receiver (ZXY-Go)	High-end differential, multi-frequency, and multi-GNSS	Position Time Speed	In-field XC skiing simulation	Horizontal plane position errors (third quartile): · Gar-920XT: 2.09 m · Cat-S5: 1.04 m · ZXY-Go: 5.29 m Vertical precision (IQR): · Gar-920XT: 2.71 m · Cat-S5: 3.89 m · ZXY-Go: 13.35 m Precision horizontal plane speed (IQR): · Gar-920XT: 0.038 $m \cdot s^{-1}$ · Cat-S5: 0.072 $m \cdot s^{-1}$ · ZXY-Go: 0.66 $m \cdot s^{-1}$ Precision time (IQR): · Gar-920XT: 0.30 s · Cat-S5: 0.13 s · ZXY-Go: 0.68 s	[83]	Larger errors skiing at low speeds, e.g., in uphill
	OptimEye Catapult device with integrated GNSS, 10 Hz		Position Time Speed	In-field XC skiing competition, classical, 10 and 15 km	Reliably detection of position, speed, and time Errors: · 1.04 m, horizontal plane position · 0.072 $m \cdot s^{-1}$, horizontal plane speed Small and light device	[24]	Increased errors at lower speeds (up to 0.36 $m \cdot s^{-1}$ at 2 $m \cdot s^{-1}$)
Emit EQ Timing system	100 Hz timing system 20 Hz Leica GNSS system		Split-time analyses according to terrain Course profile	In-field biathlon and sit-skiing races 50-60 sit-skiers/race	In-field competition Relatively large sample size	[110]	No kinematic analyses GNSS only used for course profile registration

MOVEMENT TRACKING						
2D video-based tracking	A panning 50 Hz video camera	CL CR	In-field XC skiing sprint race, freestyle	Easy to collect	[18]	· Time intensive · Delay in the sharing of data with coaches and athletes · Impractical during competition · Limited data storing · Must be perpendicular to the tracks/skier · Limited distance per camera · Limited analysis of the arm and shoulder · Manually analyses · Reduced resolution and accuracy of video recordings outside
	Two 50 Hz digital cameras	CL CR Cycle velocity	Simulated in-field XC skiing sprint race, classical	Easy to collect	[81]	
	One 30 Hz camera at a 30 m uphill and one at a flat section	CL CR	In-field 15 km XC skiing race, freestyle	Easy to collect	[45]	
	Camcorder following the skier	CL CR	In-field XC skiing simulation, freestyle Two V_{max} tests + sprint		[19]	
	Two 25 Hz digital cameras (flat and uphill section)	CT CL Duty cycle Pole and trunk inclination	15 km sit-skiing race	In-field competition on snow	[14]	
	One 90 Hz camera, recording in the sagittal plan	Poling phase Recovery phase Joint angles	In-field sprint sit-skiing race	In-field competition on snow	[109]	
	90 Hz video camera, recording in the sagittal plane	Angular velocities and accelerations	In-field sprint sit-skiing race	In-field competition on snow	[108]	

	Three 50 Hz video cameras, recording in the sagittal plane		Trunk, elbow, hip, and pole angles	In-field sit-skiing race simulation	Sit-skiing on snow	[113]	
Electronic goniometers	Goniometers, 2000 Hz		Angle, knee, elbow, and hip angles	Roller-skiing, DP on a treadmill	Unlimited capture volume	[30]	Unsuitable for measuring shoulder joint angles
	Electrogoniometers, 3000 Hz		Elbow, hip, and knee joint angles	Roller-skiing, DP on a treadmill	Accuracy: ±2° measured over a range of ± 90° Repeatability: 1° measured over a range of 90°	[86]	
	Electrogoniometers, 2000 Hz	50 Hz video camera	Knee angle	In-field XC skiing, freestyle		[87]	
Accelero-meter	Smart phone attached to the chest, 80 Hz		Automatic sub-technique classification	Roller-skiing, freestyle on a treadmill	90% accuracy	[88]	Limited dataset (438 cycles analyzed)
Pole- and ski force transducers	2000 Hz strain gauge force transducer in the pole Pedar mobile system, pressure insoles	2000 Hz AMTI force plate	CT PT_{abs} PT_{rel} PF Plantar forces	Roller-skiing, DP on a treadmill	Mean absolute error for the pole force during a poling phase: 3.8% Mean absolute error for the plantar forces during a cycle: 2.6%	[30]	Modification of the skier's equipment Expensive
	3000 Hz strain gauge load cell in the pole	AMTI force plate	CT PT ST Pole forces	Roller-skiing, DP on a treadmill	Mean absolute error during a cycle for the pole force: 2.9%	[86]	
	2000 Hz strain gauge force transducer in the pole	AMTI force plate	Pole forces Plantar ski reaction forces	In-field XC skiing, freestyle	Mean absolute errors: · Pole forces: 3.8% · Plantar forces: 2.6%	[87]	1.5 kg measurement equipment

100 Hz pedar mobile system, pressure insoles		CT, CR, CL				
1000 Hz force transducer on pole		Pole forces	Roller-skiing, DP on a treadmill		[89]	
3000 Hz strain gauge force transducer 100 Hz Pedar mobile system, pressure insoles		Pole forces Reaction forces ski CR, CL, PT Leg push-off time	Roller-skiing, DP, DIA, and V2 on a treadmill		[57]	1.5 kg measurement equipment
3000 Hz strain gauge force transducer 100 Hz Pedar mobile system, pressure insoles	AMTI force plate	Pole forces Plantar ski reaction forces CR, CL, CT	Roller-skiing, V1 freestyle on a treadmill	Mean absolute error: · Plantar forces: 2.3% · Pole forces: 2.8%	[92]	1.5 kg measurement equipment
3000 Hz strain gauge force transducer Custom-made force measurement system on the skis		CT, CR, CL PT and ST of poles and skis	XC skiing on snow, freestyle		[103]	Modification of the skier's equipment All skiers used same pair of skis
1000 Hz pole force system		Pole forces	In-field race simulation	Sit-skiing on snow	[113]	
1000 Hz strain gauge force transducer		Pole forces CT, PT, PP RP	In-field simulation at a 16 m long track,	Sit-skiing on snow	[111]	Small sample size No trunk kinematic, upper limb angles, and ROM

				sit-skiers	Showed that simulated ergometer skiing and sit-skiing on snow correspond well		Short section, same incline
	1000 Hz strain gauge force transducer		Pole forces Kinematic pattern	In-field sit-skiing simulation, 80 m track, submax and maximal skiing	Sit-skiing on snow	113	
EMG	2000 Hz, pre-gelled bipolar Ag/AgCl surface electrodes		Activity of muscles involved in DP	Roller-skiing, DP on a treadmill		30	
	2000 Hz, pre-gelled bipolar Ag/AgCl surface electrodes	Reference electrode on patella	Activity of leg muscles	Roller-skiing, DP on a treadmill		87	Complicated to employ outdoor
	Surface electrodes, 1000 Hz		Timing, duration, and amplitude of muscle activation	Roller-skiing, DP on a treadmill		89	
	Surface electromyogra-phical system, 1000 Hz	Reference electrode on acromion	Activation of arm, trunk, and back muscles	In-field simulation on a 16 m long track, sit-skiers	Sit-skiing on snow Showed that simulated ergometer skiing and sit-skiing on snow correspond well	111	Small sample size No kinematic of trunk, upper limb angles, and ROM Short section, same incline
IMU	Two IMUs, one on the chest and one on the arm		Automatic sub-technique classification	Roller-skiing, classic on a treadmill	93.9% accuracy Small and light sensors	96	Threats to the external validity of the measurements:

Six IMUs	Manually synced to video recordings from a camera placed on the skier's forehead	Automatic sub-technique classification	Classical skiing on snow, low and high intensity	Accuracy of ~97.5% Sensitivity and precision of ~100% Small and light sensors	99	· Accelerometers sensitive to gravity · Gyroscopes sensitive to drifting errors IMUs measure within a local coordinate system → unknown initial position, speed, and orientation in the global coordinate system, although inputs from other sensor's (e.g., GNSS) can strengthen external validity
Device with integrated GNSS and IMU, 100 Hz	Visually exami-nation of accelero-meter and gyroscope signals	Automatic sub-technique classification CL, CR, CT	Classical XC skiing race on snow	96% per distance accuracy Small and light sensors	24	
Two IMUs on each wrists and two on each roller-ski	Visually exami-nation against video recordings	Automatic sub-technique classification	Roller-skiing outdoor, skating	94.8 % accuracy Small and light sensors	98	
Four IMUs: Two on the wrists Two on the skis	Visually exami-nation against video recordings	Automatic sub-technique classification	Roller-skiing outdoor, classical, high intensity	98.5% accuracy Small and light sensors	97	
Six IMUs (back, arm, and ankle)	Visually exami-nation	Automatic sub-technique classification	In-field XC skiing on snow	99-100% sensitivity and precision	78	

	against video recordings					
One IMU on the wrist	Visually exami-nation against video recordings	Automatic cycle classification CL, CR, CT	In-field sit-skiing simulation, low and high intensity	95% accuracy	[13]	One LW12 sit-skier

Absolute poling time (PT_{abs}); Cross-country (XC); Cycle length (CL); Cycle rate (CR); Cycle time (CT); Diagonal stride (DIA); Differential (d-); Double dance (V2); Double poling (DP); Electromyography (EMG); Global navigation satellite systems (GNSS); Global position system (GPS); Ground reaction force (GRF); Inertial measurement unit (IMU); Locomotor winter, physically impaired sitting skier (LW); Power output (PO); Poling force (PF); Poling phase (PP); Poling time (PT); Range of motion (ROM); Real-time kinematics (RTK); Recovery phase (RP); Relative poling time (PT_{rel}); Single dance (V1); Swing time (ST).

STUDY I

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 08 February 2022
doi: 10.3389/fspor.2021.823014

Check for updates

Comparison of Race Time-Differences Between and Within Para and Able-Bodied Cross-Country Skiers

Camilla H. Carlsen, Cecilia Severin, Øyvind Sandbakk and Julia K. Baumgart*

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

Purpose: To compare differences in race time (i.e., the average percent difference in race time for each skier compared to the winner, RT_{diffs}) between female and male Para and able-bodied (AB) skiers, and to examine whether RT_{diffs} change across seasons.

Methods: Race data from World Cups (WCs), World Championships (WCHs), and Paralympic/Olympic Winter Games (PWG/OWGs) of the 2011–2020 seasons was extracted from the website of the International Paralympic Committee and the International Ski Federation. All individual distance races for female and male visually impaired standing (VI), physically impaired sitting (SIT) and standing (STAND), and AB skiers with ≥10 competitors were included in the analyses. We investigated the main effect of skiing groups (i.e., VI, STAND, SIT, and AB skiers) and sex on RT_{diffs} for top-3 and top-8 skiers. Furthermore, the main effect of season and skiing group on RT_{diffs} for top-3 and top-8 skiers were investigated. All models were adjusted for distance, skiing style (classical- and freestyle), and event type (WC, WCH, and PWG/OWG).

Results: RT_{diffs} were significantly larger in Para compared to AB skiers (top-3: 2.1 vs. 0.9%; top-8: 6.2 vs. 2.1%, all $p < 0.01$), and in female compared to male skiers (top-3: 1.8 vs. 1.3%; top-8: 4.9 vs. 3.5%, all $p < 0.05$). For top-3 skiers, RT_{diffs} did not significantly differ between the Para categories (all $p > 0.2$), while for top-8 skiers RT_{diffs} were significantly larger for VI compared to SIT and STAND (7.0 vs. 5.5 and 5.6%, respectively, all $p < 0.05$). RT_{diffs} were stable across the 2011–2020 seasons for top-3 skiers (VI: 1.7–3.6%, STAND: 1.1–2.2%, SIT: 1.0–3.9%, AB: 0.4–1.1%; all $p > 0.1$) and top-8 skiers (VI: 3.4–12.0%, STAND: 2.6–5.7%, SIT: 1.9–5.9%, AB: 0.1–1.7%; all $p > 0.1$).

Conclusion: The larger RT_{diffs} in Para compared to AB skiers indicate larger variability in performance, which are in part disability related. Female skiers displayed larger RT_{diffs} than their male counterparts, indicating larger variability in performance among the female skiers. Our results provide insights about performance demands in Para cross-country skiing, which is of relevance for coaches and skiers.

Keywords: competition, time-factor, classification, performance, Paralympic, nordic skiing

OPEN ACCESS

Edited by:
Franck Brocherie, Institut National du Sport, de l'Expertise et de la Performance (INSEP), France

Reviewed by:
Marko S. Laaksonen, Mid Sweden University, Sweden
Chiara Zoppirolli, University of Verona, Italy

****Correspondence:***
Camilla H. Carlsen
camilla.h.carlsen@ntnu.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: *26 November 2021*
Accepted: *22 December 2021*
Published: *08 February 2022*

Citation:
Carlsen CH, Severin C, Sandbakk Ø and Baumgart JK (2022) Comparison of Race Time-Differences Between and Within Para and Able-Bodied Cross-Country Skiers. Front. Sports Act. Living 3:823014. doi: 10.3389/fspor.2021.823014

INTRODUCTION

Understanding how race times differ between competing athletes is crucial for elite athletes and their coaches since they indicate the performance improvements required for winning. This insight can guide athletes in their goal setting and help coaches evaluate the training progress. Numerous studies have investigated differences in race time for able-bodied (AB) endurance athletes in a range of summer (Pyne et al., 2004; Paton and Hopkins, 2005, 2006; Nibali et al., 2011; Smith and Hopkins, 2011) and winter sports (Bullock et al., 2009; Spencer et al., 2014; Skattebo and Losnegard, 2018). However, studies on differences in race times between athletes with a disability (Para) and AB are currently limited to swimming and show larger differences among Para swimmers (Fulton et al., 2009). Even though Para cross-country (XC) skiing is one of the most popular winter Para-sports, research on differences in race time has so far only been conducted on AB skiers (Spencer et al., 2014). This research showed that differences in race time were slightly larger among top-10 female compared to male AB skiers (0.8 vs. 0.1%, respectively) (Spencer et al., 2014).

Both Para and AB skiers compete in annual World Cups (WCs), biennial World Championships (WCHs), and quadrennial Paralympic (PWGs)/Olympic Winter Games (OWGs) (IPC, 2021a). Race courses consist of undulating terrain over distances ranging from 0.8 to 20 km for Para, and 1.2 to 50 km for AB skiers. To improve competition fairness for Para skiers with different disabilities, they are classified into three different categories: (1) physically impaired sitting (SIT) skiers, (2) physically impaired standing (STAND) skiers, and (3) visually impaired standing (VI) skiers (Tweedy and Vanlandewijck, 2011; IPC, 2021a). While STAND and VI skiers compete in both the classical style and free-style, SIT skiers only compete in the classical style (IPC, 2020, 2021a).

Within the three categories, Para skiers are further divided into classes based on the functional impact the disability has on performance: LW10-12 for SIT, LW2-9 for STAND, and B1-3 for VI (IPC, 2021a). Due to often low numbers of competitors in each class, all classes in the same category compete together in a single race. Based on their class, each skier is assigned a time-factor (Vanlandewijck and Thompson, 2011; IPC, 2016; Rosso and Gastaldi, 2020), which is multiplied with the skier's actual race time to determine their adjusted race time and their final rank (Vanlandewijck and Thompson, 2011; IPC, 2016). The purpose of the time-factor is to further reduce disability-related differences in race time between skiers, so that skiers with larger functional limitations receive larger deductions in race time. While it is reasonable to assume that the differences between the adjusted race times would be smaller than the unadjusted ones, this has not yet been investigated in Para XC skiing.

In elite AB XC skiing, the average skiing speed has increased by ∼10% over the last three decades for middle- and long-distance classical and free-style races (Losnegard, 2019). Since the differences in race time have remained stable within this time period (Stöggl et al., 2009; Spencer et al., 2014), it seems that the speed increased equally for all skiers. In contrast, smaller race times differences have been reported for Para sprint runners across the 1992–2012 seasons (Grobler et al., 2015), likely due to the growing popularity of Para sports and increased numbers of participating countries and athletes. In light of this, one could speculate that the race time differences between the skiers have gotten smaller also in Para XC skiing, but this has not yet been examined.

Therefore, the primary aim of this study was to compare differences in race time (RT_{diffs}) between female and male Para and AB XC skiers. To investigate the effects of the time-factor on RT_{diffs} for the Para skiers, analyses were done both with the adjusted and unadjusted race times. The secondary aim was to examine how RT_{diffs} changed across the 2011–2020 seasons. For the primary aim, we hypothesized to find: (1) larger RT_{diffs} among Para compared to AB skiers, (2) larger RT_{diffs} among female skiers compared to male skiers, and (3) smaller RT_{diffs} with adjusted compared to the unadjusted race times. For the secondary aim, we hypothesized that RT_{diffs} for the Para skiers were reduced from the 2011 to the 2020 season.

MATERIALS AND METHODS

Overall Design

Race data of Para and AB skiers during all WCs, WCHs, and PWG/OWGs were analyzed for the 2011–2020 seasons. The data were limited to the 2011–2020 seasons, as competition results for Para skiers have been systematically stored by the IPC since the 2010/2011 season. Lower-level skiers may disproportionally influence RT_{diffs}, and lead to larger differences across the competition field compared to those seen among the medalists. Accordingly, RT_{diffs} for each individual race were calculated for both the top-8 and the top-3 skiers for all skiing groups (VI, STAND, SIT, and AB skiers).

Data Extraction

Official race data of Para and AB skiers was extracted from the IPC (IPC, 2021b) and FIS websites (FIS, 2021), respectively. The IPC and FIS obtain informed consent from all competing athletes to publish the race data online. Prior to any processing, we de-identified the data through the removal of identifiable information. The data extraction and processing were approved by the Norwegian Centre for Research Data (ID 765557).

For every time-trial competition, sex, race time, final rank, race distance, skiing style, event type, and season were extracted for each Para and AB skier. Additionally, information on the skiing category and class were extracted for the Para skiers. To obtain the unadjusted race times, each adjusted race time was divided by the class-specific time-factor of the 2019/2020 season. The time-factor is evaluated every season by the IPC and while minor changes may have been made during the 2011 to 2020 seasons, these are unlikely to have a major effect on our calculations. Only data from individual short- and middle-distance time-trial races were included in the analysis. Data of the sprint- and long-distance races were excluded since these are mass start competitions for AB skiers, and are known to affect the pacing strategy and speed, and thereby race times (Thiel et al., 2012; Hanley, 2015; Losnegard, 2019). The division of short- and middle distances was done as per IPC (IPC, 2020) and FIS (FIS,

TABLE 1 | The number of races included in the analyses divided for Para (SIT: physically impaired sitting skiers, STAND: physically impaired standing skiers, and VI: visually impaired standing skiers) and AB skiers by sex, skiing style, and distance.

	Skiers	Races (No.)	Sex	Races (No.)	Skiing style	Races (No.)	Distance	Length (km)	Races (No.)
Para	SIT	61	M	37	Classical	37	Short	5	8
							Middle	10	29
			F	24	Classical	24	Short	5	5
							Middle	7.5	19
	STAND	46	M	25	Classical	17	Short	7.5	4
							Middle	12.5	13
					Free-style	8	Short	7.5	2
							Middle	12.5	6
			F	21	Classical	10	Short	5	2
							Middle	10	8
					Free-style	11	Short	5	3
							Middle	10	8
	VI	24	M	18	Classical	9	Short	7.5	2
							Middle	12.5	7
					Free-style	9	Short	7.5	1
							Middle	12.5	8
			F	6	Classical	4	Short	5	2
							Middle	10	2
					Free-style	2	Short	5	–
							Middle	10	2
	AB	104	M	49	Classical	23	Short	10	4
							Middle	15	19
					Free-style	26	Short	10	8
							Middle	15	18
			F	55	Classical	17	Short	5	3
							Middle	10/15	14
					Free-style	38	Short	5	9
							Middle	10/15	29

F, Female skiers; M, Male skiers.

2020) regulations (**Table 1**). It should be noted that the SIT skiers only compete in the classical technique so their data is limited to this skiing style.

Data Processing

Races with fewer than 10 competitors were excluded (58, 39, 29, and 1% for VI, STAND, SIT, and AB skiers, respectively) to reduce inflation of RT_{diffs} due to lower-level skiers. For the same reason, only results of the top-8 skiers were included and the results of the skiers ranked 9th and 10th place were excluded. The percent RT_{diff} between the winner and the other seven skiers (i.e., 2nd to 8th rank) were calculated for all remaining races. For the Para skiers, this was done for both the adjusted and unadjusted race times.

Statistical Analysis

All statistical analyses were performed using linear mixed modeling procedures in Stata 16.1 (StataCorp LLC, College Station, Texas, USA). For the primary aim, we investigated the main effect of skiing group (i.e., VI, STAND, SIT, and AB skiers) and sex, as well as the interaction between skiing group*sex on RT_{diffs} for the top-3 and top-8 skiers. In the latter analyses, only the adjusted race times were used for the Para skiers. Separate analyses were performed to investigate whether RT_{diffs} differed between Para XC skiing groups when using the unadjusted or adjusted race times. For the secondary aim, we investigated the main effect of season and skiing group, as well as the interaction between the season*skiing group on RT_{diffs} for the top-3 and top-8 skiers. For these analyses, the adjusted race times were used for the Para skiers. A separate analysis was performed for the Para XC skiing groups to investigate whether the RT_{diffs} between seasons were larger when using the unadjusted race times compared to the adjusted race times. All the models were adjusted for the fixed factors distance (short or middle), skiing style (classical or free-style), and event type (WC, WCH, or PWG/OWG). *Post-hoc* analyses using the Bonferroni's correction were performed for pairwise comparisons of the estimated marginal means for the skiing group, skiing group*sex, and skiing group*season. Visual examination of Q–Q plots, and plots comparing residual vs. predicted values indicated no deviation from normality. Results are reported as mean ± 95% CI if not stated otherwise. An alpha-value of 0.05 was used to indicate statistical significance.

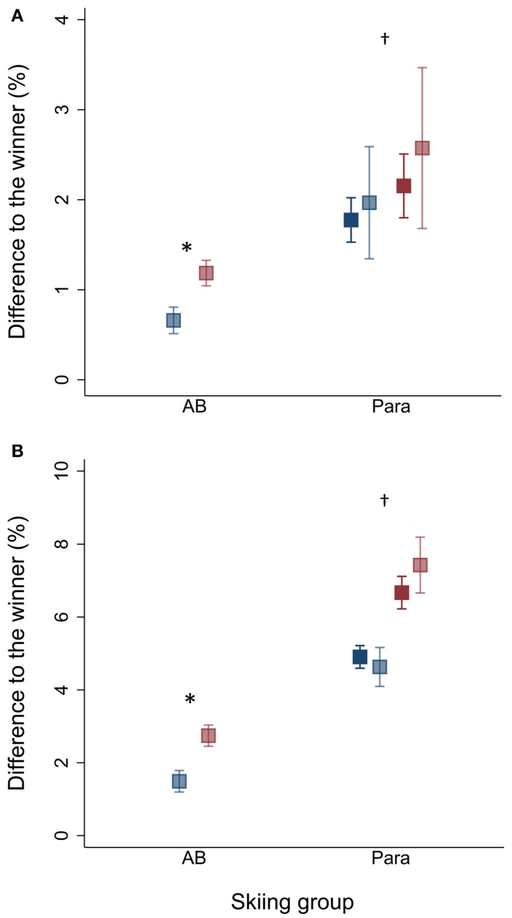


FIGURE 1 | Estimated adjusted (dark color) and unadjusted (light color) differences in race time (RT_{diffs}) for **(A)** top-3 and **(B)** top-8 female (red) and male (blue) Para and able-bodied (AB) skiers. Presented as mean ± 95% CI. *Significantly larger adjusted RT_{diffs} for female compared to male skiers within same skiing group, $p < 0.05$. †Significantly different from AB skiers, $p < 0.01$.

RESULTS

Differences in Race Time Across Skiing Groups and Sex

When adjusted for sex, RT_{diffs} were significantly larger in Para compared to AB for both the top-3 and top-8 skiers (top-3: 2.1 vs. 0.9%; top-8: 6.2 vs. 2.1%, all $p < 0.01$) (**Figure 1**). There were no significant differences in RT_{diffs} among the top-3 skiers across the Para categories (all $p > 0.2$). However, RT_{diffs} among the top-8 skiers were significantly larger for VI compared to STAND and SIT (7.0, 5.5, and 5.6%, respectively; all $p < 0.05$) (**Figure 2**).

Furthermore, when adjusted for skiing groups, RT_{diffs} were significantly larger among female compared to male skiers (top-3: 1.8 vs. 1.3%; top-8: 4.9 vs. 3.5%, all $p < 0.05$) (**Figure 2**). RT_{diffs} among top-3 skiers were significantly larger for female compared to male AB skiers (1.3 vs. 0.6%, $p < 0.02$), while there were no significant differences between female and male Para skiers within any of the Para categories (all $p > 0.1$). RT_{diffs} amongst the top-8 skiers were significantly larger for female compared to male SIT (7.0 vs. 4.5%, $p < 0.001$) and AB (2.8 vs. 1.6%, $p < 0.001$).

There were no significant differences between adjusted and unadjusted RT_{diffs} for neither the top-3 nor top-8 skiers in any of the Para categories (all $p > 0.1$) (**Figure 2**).

Differences in Race Time Across Seasons

When adjusted for sex and skiing group, RT_{diffs} for the top-3 and top-8 skiers did not significantly differ across the seasons 2011–2020 for the top-3 skiers (VI: 3.6–2.6%, STAND: 2.2–1.6%, SIT: 1.0–3.9%, AB: 1.0–1.1%, all $p > 0.1$) and top-8 skiers (VI: 12.0–4.2%, STAND: 2.6–3.5%, SIT: 1.9–5.9%, AB: 1.5–0.9%, all $p > 0.1$). As such, the comparisons of RT_{diffs} between skiing groups and sex provided in the previous section are similar across seasons. Furthermore, there was no significant difference between adjusted and unadjusted RT_{diffs} for the top-3 and top-8 skiers across the seasons 2011–2020 (all $p > 0.1$) (**Figure 3**).

DISCUSSION

This study investigated RT_{diffs} for the top-3 and top-8 female and male Para and AB skiers. Para skiers displayed larger RT_{diffs} than AB skiers, and female skiers displayed larger RT_{diffs} than male skiers. There were no significant differences between RT_{diffs} when using the adjusted or unadjusted race times, but the variability of RT_{diffs} within the Para categories was slightly reduced after the time-factor adjustments. RT_{diffs} were stable across the last 10 seasons, but displayed a slightly less variable pattern for adjusted race times compared to unadjusted race times.

Differences in Race Time Across the Skiing Groups

This is the first study to examine RT_{diffs} between Para and AB skiers, as well as between the three Para categories. In support of our primary hypothesis, Para displayed larger RT_{diffs} compared to AB skiers, which also supports the earlier study on elite Para and AB swimmers (Fulton et al., 2009). The authors related these findings to the effects of disability on performance, more limited international race experience, and a slower evolution of the sport (Daly and Vanlandewijck, 1999; Fulton et al., 2009), which may also explain the larger RT_{diffs} in our study. Additionally, the lower number of competitors in Para XC skiing means that a larger proportion will be included in the top-8. The range of performance levels in the top-8 is therefore likely larger compared to AB skiers, which contributes to larger RT_{diffs}. This is supported by our observation that the Para skiers had a ~4 percentage points increase of RT_{diffs} from the top-3 skiers to top-8 skiers (from 2.1 to 6.2%), while the AB skiers only had a ~1 percentage point increase (from 0.9 to 2.1%).

Notably, VI displayed significantly larger RT_{diffs} compared to SIT and STAND for the top-8 skiers, which likely can be attributed to differences between the male competitors

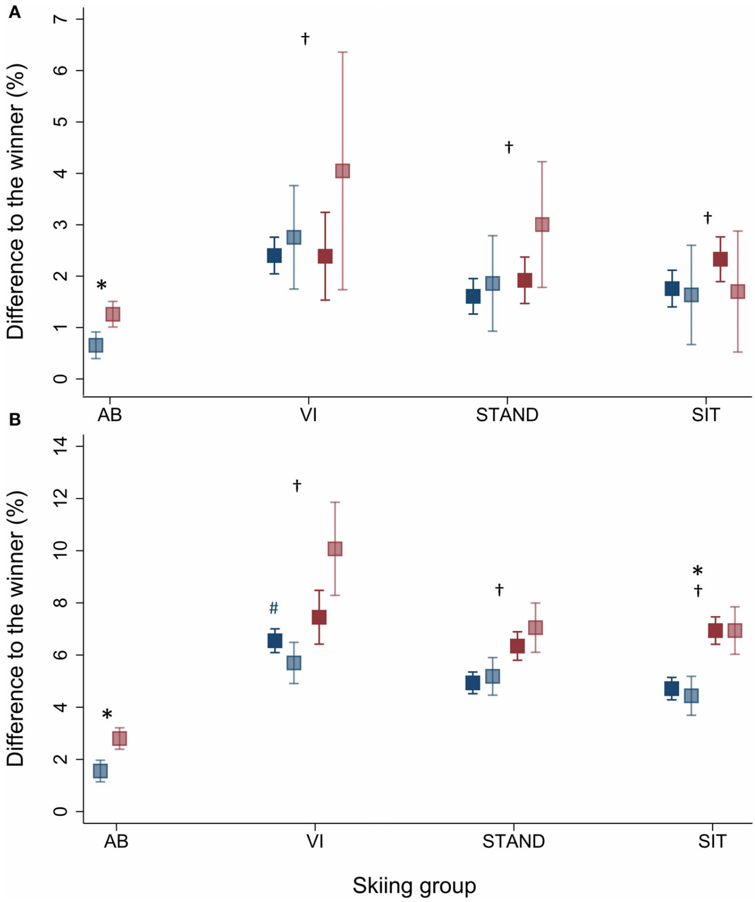


FIGURE 2 | Estimated adjusted (dark color) and unadjusted (light color) differences in race time (RT_{diffs}) for **(A)** top-3 and **(B)** top-8 female (red) and male (blue) Para (VI: visually impaired standing skiers, STAND: physically impaired standing skiers, and SIT: physically impaired sitting skiers) and able-bodied (AB) skiers. Presented as mean ± 95% CI. *Significantly larger RT_{diffs} for female compared to male skiers within same skiing group, $p < 0.05$. †Significantly different from AB skiers, $p < 0.01$. #Significantly larger adjusted RT_{diffs} for male VI compared to male STAND and SIT skiers, $p < 0.05$.

(**Figure 2B**). Larger disability-related performance differences between the male Para XC skiing categories may be due to a larger proportion of the male VI competitors in the lower classes, which include skiers with the largest functional limitations. In addition, there is a possibility that the general competitiveness (i.e., not related to the disability) may be lower in male VI skiers compared to SIT and STAND competitors, however, the reasons for such differences are currently unclear.

In contrast to our hypothesis, RT_{diffs} for the Para skiers have remained relatively stable across the last 10 seasons. This is similar to previous findings in AB XC skiing (Stöggl et al., 2009; Spencer et al., 2014), but differs from the observation of closer race times in Para sprint running between 1992 and 2012 (Grobler et al., 2015). Two lines of reasoning could explain the stable RT_{diffs} across seasons among the Para skiers. Either a performance development has not happened during the examined time period (i.e., 2011–2020), or the performance development was there but similar for all levels of the Para skiers, leaving RT_{diffs} unchanged.

Differences in Race Time Between Female and Male Skiers

In support of our hypothesis, RT_{diffs} were larger in female skiers compared to male skiers. Notably, this difference was significant only for the AB skiers, while there were no significant differences between the Para skiers which are likely attributed to the large variability and small sample sizes within the female

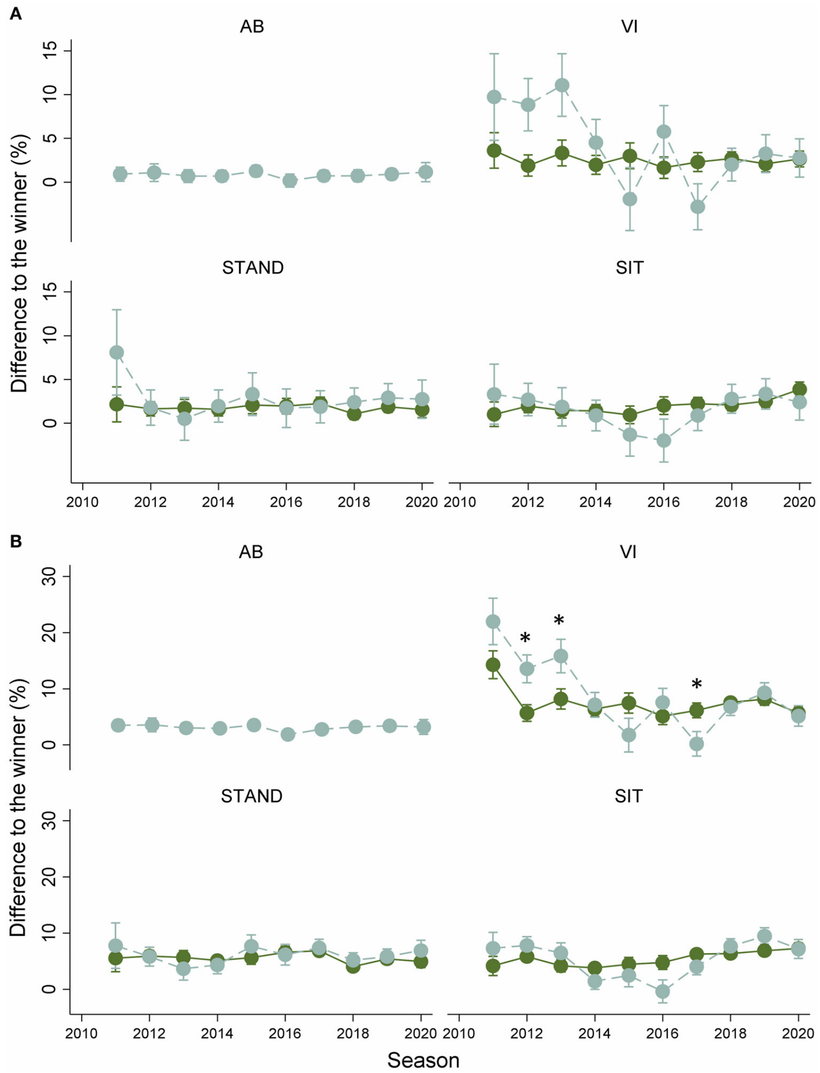


FIGURE 3 | Estimated differences in race time (RT_{diffs}) for **(A)** top-3 and **(B)** top-8 of adjusted (dark green solid line) and unadjusted (light green dashed line) race times of Para (VI: visually impaired standing skiers, STAND: physically impaired standing skiers, and SIT: physically impaired sitting skiers), and able-bodied (AB) skiers for the 2011–2020 seasons. Values presented as an annual average ± 95% CI. *Significant difference between adjusted and unadjusted RT_{diffs}, $p < 0.05$.

Para skiers. Larger RT_{diffs} in female athletes have previously been demonstrated in AB XC skiing (Stöggl et al., 2009; Spencer et al., 2014), skeleton (Bullock et al., 2009), and slalom kayaking (Nibali et al., 2011), and explained by lower performance levels of the best female compared to the best male athletes (Bullock et al., 2009; Spencer et al., 2014). The same seems to be the case for female Para skiers, especially given that female races typically have half the number of competing skiers than male races do (i.e., 24 female Para skiers vs. 42 male Para skiers on average in each category).

Adjusted and Unadjusted Differences in Race Times

For the top-3 and top-8 skiers, neither VI, STAND, nor SIT skiers displayed a significant difference between adjusted and unadjusted RT_{diffs}. This is contrary to our hypothesis and likely attributed to the large variability in RT_{diffs}, especially for the unadjusted RT_{diffs}. While not being significantly different, unadjusted times still displayed a more variable pattern across the last ten seasons compared to the corresponding adjusted times. Accordingly, the time factor appears to contribute to less variability in RT_{diffs} among the Para skiers, especially for VI (**Figures 3A,B**). Speculatively, the more variable patterns in RT_{diffs} based on the unadjusted race times for VI may be related to a larger proportion of skiers in lower functional classes. Future investigations should look into the differences between adjusted and unadjusted RT_{diffs} not only within Para XC skiing categories, but also within classes.

Methodological Considerations

In the current study, the calculations for RT_{diffs} differed slightly from other studies investigating differences in race time [e.g., AB XC skiing (Spencer et al., 2014) and Para swimming (Fulton et al., 2009)]. In these studies, race times were log-transformed prior to analyses, which yield the variability and differences as percentages of the mean when back-transformed. In this study, the differences in race times as percentages were directly calculated from the absolute race times before the analyses. Therefore, caution is warranted when directly comparing our results with findings from other studies. In addition, in the current study, the time-factor system in place at the 2019/2020 seasons was employed for all ten seasons. While the time-factor is evaluated every season by the IPC (IPC, 2016), and minor changes may have been made during the 2011–2020 seasons, these are unlikely to affect the general outcome of the comparisons between adjusted and unadjusted RT_{diffs}.

CONCLUSION

Para skiers displayed larger RT_{diffs} compared to the AB skiers. This is likely due to disability-related differences in performance among the Para skiers and fewer competing skiers compared to the AB equivalents. The larger RT_{diffs} for female skiers compared to male skiers were predominantly due to differences within the AB skiers, and lower performance levels in AB females. While differences were also larger in female compared to male Para skiers, this did not reach statistical significance, likely due to variability and small sample sizes within the female Para skiers. Using adjusted or unadjusted race times did not affect RT_{diffs} significantly, although the adjusted times were less variable and thus indicating that the time factor contributes to lower RT_{diffs} between the Para skiers. These findings are important for athletes and coaches during the goal-setting process and for evaluating the training progress, as they indicate the performance improvement needed to gain a better rank or win the race. In future studies, the distribution of classes within the categories, and its relationship to the differences in race time, should be investigated.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Norwegian Centre for Research Data. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

CHC, JKB, and ØS all contributed to the conceptualization and design of the study. CHC and JKB acquired the data. CHC, JKB, and CS interpreted the results. CHC analyzed the data and drafted the study with all authors critically revising it for important intellectual content. All authors approved the final version to be published.

FUNDING

This study was funded by the Centre for Elite Sports Research, Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology, Trondheim, Norway.

ACKNOWLEDGMENTS

The authors would like to thank Roy Mulder for his expertise and help extracting the race data of AB XC skiing from FIS.

REFERENCES

Bullock, N., Hopkins, W. G., Martin, D. T., and Marino, F. E. (2009). Characteristics of performance in skeleton World Cup races. *J. Sports Sci.* 27, 367–372. doi: 10.1080/02640410802613425

Daly, D. J., and Vanlandewijck, Y. C. (1999). Some criteria for evaluating the "fairness" of swimming classification. *Adapt. Phys. Activ. Q.* 16, 271–289. doi: 10.1123/apaq.16.3.271

FIS. (2020). *The International Ski Competition Rules (ICR)*. Oberhofen: Book II Cross-country, p. 95.

FIS. (2021). *The International Ski Federation Calender and Results*. Available online at: https://www.fis-ski.com/DB/cross-country/calendar-results.html?noselection=true.Place, P.ublished (accessed August 21, 2021).

Fulton, S. K., Pyne, D., Hopkins, W. G., and Burkett, B. (2009). Variability and progression in competitive performance of Paralympic swimmers. *J. Sports Sci.* 27, 535–539. doi: 10.1080/02640410802641418

Grobler, L., Ferreira, S., and Terblanche, E. (2015). Paralympic sprint performance between 1992 and 2012. *Int. J. Sports Physiol. Perform.* 10, 1052–1054. doi: 10.1123/ijspp.2014-0560

Hanley, B. (2015). Pacing profiles and pack running at the IAAF World Half Marathon Championships. *J. Sport Sci.* 33, 1189–1195. doi: 10.1080/02640414.2014.988742

IPC. (2016). *Explanatory guide to Paralympic Classification—Paralympic winter sports*.
IPC. (2020). *World Para Nordic Skiing Homologation Guide*.
IPC. (2021a). *The International Paralympic Committee World Para Snow Sports.* Available online at: https://www.paralympic.org/nordic-skiing/about.Place. (accessed *February* 24, 2021).
IPC. (2021b). *International Paralympic Committee.* Available online at: https://www.paralympic.org/Place. (accessed September 10, 2021).
Losnegard, T. (2019). Energy system contribution during competitive cross-country skiing. *Eur. J. Appl. Physiol.* 19:4158. doi: 10.1007/s00421-019-04158-x
Nibali, M., Hopkins, W. G., and Drinkwater, E. (2011). Variability and predictability of elite competitive slalom canoe-kayak performance. *Eur. J. Sport Sci.* 11, 125–130. doi: 10.1080/17461391.2010.487121
Paton, C. D., and Hopkins, W. G. (2005). Competitive performance of elite Olympic-distance triathletes: reliability and smallest worthwhile enhancement. *Sport Sci.* 9, 1–5. Available online at: sportsci.org/jour/05/wghtri.htm
Paton, C. D., and Hopkins, W. G. (2006). Variation in performance of elite cyclists from race to race. *Eur. J. Sport Sci.* 6, 25–31. doi: 10.1080/17461390500422796
Pyne, D., Trewin, C., and Hopkins, W. G. (2004). Progression and variability of competitive performance of Olympic swimmers. *J. Sports Sci.* 22, 613–620. doi: 10.1080/02640410310001655822
Rosso, V., and Gastaldi, L. (2020). Towards Beijing 2022: discussion on the growth in size of paralympic winter games in terms of participating data from örnsköldvik 1976 to pyeongchang 2018. *J. Hum. Sport Exerc*. 20:13. doi: 10.14198/jhse.2021.164.13
Skattebo, Ø., and Losnegard, T. (2018). Variability, predictability, and race factors affecting performance in elite biathlon. *Int J Sports Physiol Perform* 13, 313–319. doi: 10.1123/ijspp.2017-0090
Smith, T. B., and Hopkins, W. G. (2011). Variability and predictability of finals times of elite rowers. *Med. Sci. Sports Exer.* 43, 2155–2160. doi: 10.1249/MSS.0b013e31821d3f8e
Spencer, M., Losnegard, T., Hallén, J., and Hopkins, W. G. (2014). Variability and predictability of performance times of elite cross-country skiers. *Int. J. Sports Physiol. Perform.* 9, 5–11. doi: 10.1123/ijspp.2012-0382
Stöggl, T., Stöggl, J., and Muller, E. (2009). "Competition analysis of the last decade (1996– 2008) in cross-country skiing," in *Science and Skiing IV*, eds. E. Muller and T. Stöggl. Maidenhead, UK: Meyar and Meyar Sport.
Thiel, C., Foster, C., Banzer, W., and De Koning, J. (2012). Pacing in Olympic track races: competitive tactics versus best performance strategy. *J. Sports Sci.* 30, 1107–1115. doi: 10.1080/02640414.2012.701759
Tweedy, S. M., and Vanlandewijck, Y. C. (2011). International Paralympic Committee position stand-background and scientific principles of classification in Paralympic sport. *Br. J. Sports Med.* 45, 259–269. doi: 10.1136/bjsm.2009.065060
Vanlandewijck, Y.C., and Thompson, W. R. (2011). *The Paralympic Athlete: Handbook of Sports Medicine and Science*. UK: Wiley-Blackwell.

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 II

sensors

MDPI

Article

Framework for In-Field Analyses of Performance and Sub-Technique Selection in Standing Para Cross-Country Skiers

Camilla H. Carlsen [1,*], Julia Kathrin Baumgart [1], Jan Kocbach [1,2], Pål Haugnes [1], Evy M. B. Paulussen [1,3] and Øyvind Sandbakk [1]

1 Centre for Elite Sports Research, Department of Neuromedicine and Movement Science, Faculty of Medicine and Health Sciences, Norwegian University of Science and Technology, 7491 Trondheim, Norway; julia.k.baumgart@ntnu.no (J.K.B.); jan.kocbach@ntnu.no (J.K.); pal.haugnes@ntnu.no (P.H.); Evy.paulussen@mumc.nl (E.M.B.P.); oyvind.sandbakk@ntnu.no (Ø.S.)
2 NORCE Norwegian Research Centre AS, 5008 Bergen, Norway
3 Faculty of Health, Medicine & Life Sciences, Maastricht University, 6200 MD Maastricht, The Netherlands
* Correspondence: camilla.h.carlsen@ntnu.no; Tel.: +47-452-40-788

Abstract: Our aims were to evaluate the feasibility of a framework based on micro-sensor technology for in-field analyses of performance and sub-technique selection in Para cross-country (XC) skiing by using it to compare these parameters between elite standing Para (two men; one woman) and able-bodied (AB) (three men; four women) XC skiers during a classical skiing race. The data from a global navigation satellite system and inertial measurement unit were integrated to compare time loss and selected sub-techniques as a function of speed. Compared to male/female AB skiers, male/female Para skiers displayed 19/14% slower average speed with the largest time loss (65 ± 36/35 ± 6 s/lap) found in uphill terrain. Female Para/AB skiers utilized DP, DK, and DIA, 61/43%, 15/10%, and 25/47% of the distance at low speeds, respectively, while the corresponding numbers for male Para/AB skiers were 58/18%, 1/13%, and 40/69%. At higher speeds, female Para/AB skiers utilized DP and OTHER, 26/52% and 74/48% of the distance, respectively, while corresponding numbers for male Para/AB skiers were 29/66% and 71/34%. This indicates different speed thresholds of the classical sub-techniques for Para than AB skiers. The framework provides a point of departure for large-scale international investigations of performance and related factors in Para XC skiing.

Keywords: micro-sensor technology; GNSS; IMU; disability; heterogenous group; cross-country skiing race; performance analysis; sub-technique classification; time factor

Citation: Carlsen, C.H.; Kathrin Baumgart, J.; Kocbach, J.; Haugnes, P.; Paulussen, E.M.B.; Sandbakk, Ø. Framework for In-Field Analyses of Performance and Sub-Technique Selection in Standing Para Cross-Country Skiers. *Sensors* **2021**, *21*, 4876. https://doi.org/10.3390/s21144876

Academic Editor: Vesa Linnamo

Received: 17 June 2021
Accepted: 14 July 2021
Published: 17 July 2021

1. Introduction

Para cross-country (XC) skiing is a winter sport performed by skiers with different disabilities. Depending on their disability, Para XC skiers compete in three categories, which are further divided into classes, based on the functional impact of the disability on XC skiing performance: (1) physically impaired sitting skiers (classes: LW10–12), (2) physically impaired standing skiers (classes: LW2–9), and (3) visually impaired standing skiers (classes: B1–3) [1,2]. Additionally, within each category, a class-specific time factor is used to calculate the final race time [1,2].

Physically impaired standing XC skiers constitute a heterogenous group of skiers with different disabilities, which range from having an amputation to muscle weakness or loss of muscle control [1,2]. Similar to able-bodied (AB) XC skiers, standing Para XC skiers compete within the classical and skating styles in race courses consisting of undulating terrain with uphill, flat, and downhill segments [3]. The varying terrain during XC skiing races leads to substantial variation in speed, which is regulated by selection of pacing strategies, sub-techniques, and related kinematic patterns [4–7]. In the classical style, XC skiers alternate between double poling (DP), which is used at higher speeds on a wide range of inclines [8,9], kick double poling (DK), which is used at moderate speeds in the transition between different terrains [10], diagonal stride (DIA), which is primarily used at low speeds in moderate to steep uphill terrain [11,12], and the herringbone technique (HRB), which is used at low speeds in very steep uphill terrain [13]. During downhill sections, the skiers employ the tuck position without pole and leg actions, and various turn techniques are adapted to manage turning [4,14]. The choice of sub-technique and regulation of kinematic patterns is complex and influenced by individual preferences, internal, and external factors [6,11,12,15–18]. In classical AB XC skiing, it has been suggested that there are speed [6,17,18] and incline [11,12,16] thresholds for the use of the sub-techniques. Additionally, the skiers' physical capacity will influence the speed and choice of sub-technique [19,20]. In this context, the ability to use the different sub-techniques may additionally be dependent on functional limitations related to the individual disability among standing Para XC skiers. Accordingly, the sub-technique selected at different speeds may differ between standing Para and AB XC skiers.

Related to determination of the above parameters, micro-sensor technology has allowed detailed in-field performance analyses with continuous speed and time tracking, as well as automatic sub-technique classification, and is widely used among AB XC skiers [6,15,21]. However, in standing Para XC skiing, analyses of in-field performance or sub-technique distribution have not yet been done. Accordingly, a framework for such analyses would be beneficial for providing new insights into the technical and tactical aspects, as well as the effect of terrain and external conditions on the time factor, related to standing Para XC skiing performance.

Therefore, the aim of this study was to evaluate the feasibility of a framework based on micro-sensor technology for detailed analyses of in-field performance and sub-technique selection in Para XC skiing by using this framework in case-series to descriptively compare performance-related parameters between elite standing Para and AB XC skiers during a classical skiing race.

2. Materials and Methods

2.1. Participants

Three elite standing Para XC skiers (two male B3 skiers, one female LW4 skier) of the Norwegian national team, and nine elite AB XC skiers (five men, four women) of the Norwegian B national team participated in the study (Table 1). The male B3 skiers had 10% vision and were accompanied by a personal guide during the race. The female LW4 skier had linear scleroderma with reduced leg length, joint mobility, muscle mass, and strength in the one leg. Due to a limited number of elite standing Para XC skiers within the same category, AB XC skiers were used as reference to evaluate the feasibility of the framework. Among the male AB XC skiers, there was one participant with missing data due to complications with tracking during the race and one with an unfinished race. Their data were omitted and data of three male and four female AB XC skiers were included in the analyses. All participants signed an informed consent form and were made aware that they could withdraw from the study at any point without providing an explanation. The study was approved by the Norwegian Centre for Research Data (ID 49865/3/IJJ) and conducted in line with the Declaration of Helsinki.

Table 1. Age, body-mass, and training volume (mean ± SD) of the three Para and seven able-bodied (AB) XC skiers included in the analyses.

Parameter	Paralympic		Able-Bodied	
	Men (n = 2)	**Woman (n = 1)**	**Men (n = 3)**	**Women (n = 4)**
Age (years)	24.0 ± 2.8	19.0	25.0 ± 1.5	23.5 ± 1.3
Body-mass (kg)	70.5 ± 1.9	61.0	83.0 ± 2.0	63.5 ± 4.1
Training volume (hours·week^{-1})	13.5 ± 5.0	11.0	16.2 ± 1.0	14.5 ± 1.0

2.2. Design

During a national competition, participants performed a time-trial XC skiing race on snow using the classical style. The time-trial was performed on a 2.5 km race course, where female Para and AB XC skiers raced 10 km (4 × 2.5 km) and male Para and AB XC skiers raced 15 km (6 × 2.5 km), in accordance with the International Ski Federation regulations (Figure 1). During the race, each Para and AB XC skier was continuously tracked with a Catapult device (OptimEye S5, Catapult Innovations, Melbourne, Australia) with integrated 10 Hz global navigation satellite system (GNSS) receiver and an inertial measurement unit (IMU) providing 100 Hz triaxial accelerometer and gyroscope data, positioned in a tight fitting-vest on the skier's upper back under the race bib. All XC skiers raced on the same day. The time-trials started in the morning, with the female AB XC skiers racing first followed by the male AB XC skiers. Thereafter, the female and male Para XC skiers completed their race within the same time range. The start interval between each Para and AB XC skier was 30–60 s. Every athlete used their own ski equipment, including skis, poles, boots, and ski base material (including grinds, structure, and waxing), with adjustments being made by each team's waxing crew according to individual preferences and daily conditions. The weather conditions were stable throughout the day, with a snow temperature of −12 °C and an air temperature between −4 to −7 °C during all the races. The snow friction was measured as 0.023 in the middle of the day. The course was covered with hard-packed snow and machine-prepared directly before the races of the AB and Para XC skiers.

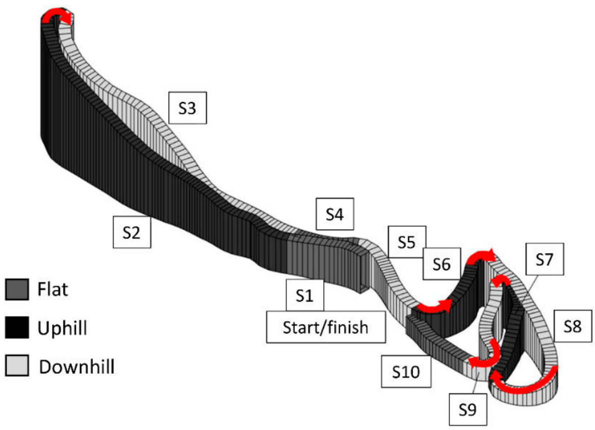


Figure 1. The 2.5 km XC skiing race course divided into the 10 segments according to the elevation difference, including three uphill, three flat, and four downhill segments. Six turns were distributed over the 2.5 km lap (red arrow). With different placement of the start and finish, there is a gap in the 2.5 km course, which was removed from the analyses. (S) Segment (length (meter), incline range (%)); S1: 131 m, −2.6–1.6%; S2: 543 m, 1.7–12.4%; S3: 509 m, −11.7–0.2%; S4 100 m, 0.7–2.8%; S5: 156 m, −6.0–0.0%; S6: 166 m, 1.3–12.7%; S7: 339 m, −8.5–−0.4%; S8: 200 m, 1.2–16%; S9: 183 m, −10.1–−1.0%; S10: 138 m, 0.0–1.6%.

2.3. Measurements

Time, positioning, altitude, and movement data for all Para and AB XC skiers were measured continuously during the race with the Catapult devices. The speed data were derived from time differentiation of the position data. Prior to the data collection, the Catapult devices were placed outside in an open space for a minimum of 10 min to ensure GNSS lock and allow acquisition of satellite signals. Recently, Gløersen et al. [22] have validated the Catapult devices for position, speed, and time analyses in AB XC skiing against a geodetic, multi-frequency receiver, with a horizontal plane position error of 1.04 m (third quartile, Q3), horizontal plane speed of 0.072 m·s^{-1} (IQR), and time precision between 0.13–0.36 s. Similar accuracy is expected when using the Catapult devices for analysis of performance as done in the current study.

2.4. Data Analysis

The length and elevation profile of the race course were obtained from the GNSS data measured with the Catapult devices that were used to track the Para and AB XC skiers. Based on the positioning and altitude data, the course was divided into segments consisting of either uphill, flat, and downhill terrain. Each segment began and ended with an evident change in the gradient of the course. The uphill and downhill segments were characterized by a minimum elevation difference of 4 m from the beginning to the end of the segment. Undulating terrain with a smaller elevation difference between adjacent uphill, flat, and downhill segments were merged into one single flat segment. Overall, the 2.5 km course was divided into 10 segments, with three uphill, three flat, and four downhill segments that made up 37%, 15%, and 48% of the course, respectively. Additionally, the 2.5 km course included six turns (Figure 2). Different placements of the start and finish of the race resulted in a gap in the 2.5 km course, which was removed from the analyses. The actual distance covered for each segment was calculated using the elevation difference from the beginning to the end of the segment and the horizontal length of the segment.

Data of speed and time were interpolated by distance for each lap for both Para and AB XC skiers. Further, the average speed and time over the four or six laps were calculated and used in the analyses. In order to compare Para and AB XC skiers, average values of speed and time were calculated for each group of female and male AB XC skiers. Furthermore, the continuous speed and time differences between the male Para and male AB XC skiers and between the female Para and female AB XC skiers were calculated. The proportion of time in the different terrains was calculated for each Para XC skier, the female, and the male AB XC skiers (mean ± standard deviation (SD)).

From the movement data of Para and AB XC skiers, measured by IMUs in the Catapult devices, automatic sub-technique classification was done by employing a K-Nearest Neighbour algorithm while using a 2 s sliding window approach (200 samples) with 95% overlap [15]. The classifier uses the low-pass filtered z-components of the accelerometer and gyroscope data as input, with the z-axis defined in the frontal direction of the participant. The same classifier was used for all skiers. The classifier was validated on AB XC skiers with a per-distance classification accuracy of 96% [6,21,23]. To apply the framework and accompanying algorithms to Para XC skiers with similar accuracy, visual examination of the classification was conducted by comparing the graphical representation of filtered accelerometer and gyroscope signals with examples that typically represent the various sub-techniques. Thereby, around 10% of the cycles from the automatic classification were manually corrected. The sub-techniques were classified as DP, DK, DIA (including both DIA and HRB), and OTHER. OTHER primarily included the tuck position, but also turn techniques and cycles that did not fulfill the above-specified criteria. At higher speeds (i.e., 7 to 10 $m \cdot s^{-1}$), OTHER almost solely contained the tuck position.

2.5. Statistical Analysis

In this case-series, descriptive comparison was made for speed, time, and sub-technique distribution between the Para and AB XC skiers, exemplifying the feasibility of the framework based on micro-sensor technology employed in the field for Para XC skiing. Data processing and calculations were done using MATLAB R2018a (version 9.7.0.1190202, MathWorks, Natick, MA) and Microsoft Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA).

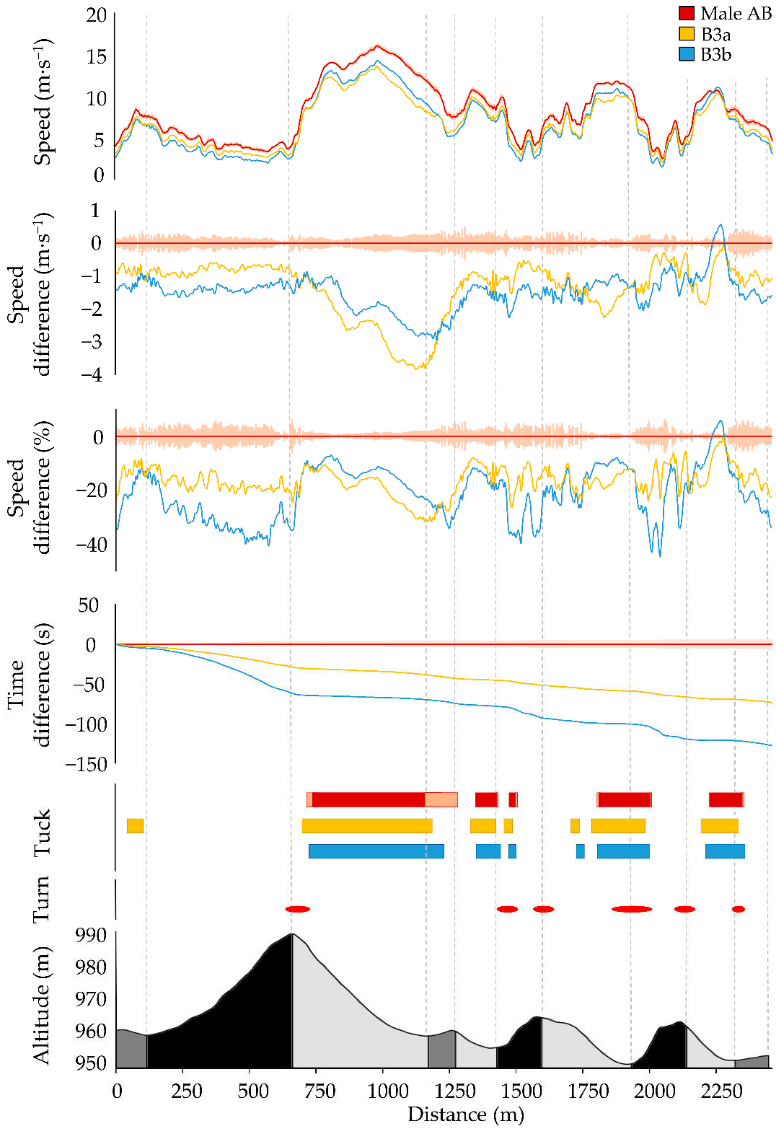


Figure 2. Comparison of average male AB XC skiers (dark red; standard deviation light pink), male B3a XC skier (yellow), and male B3b XC skier (blue) for the six laps during the race with respect to average speed, absolute speed difference, relative speed difference, accumulated time difference, and tuck. Course details are visualized in the lower part of the figure; turns (red dashes) and altitude profile of the 2.5 km race course, with uphill (black), flat (dark gray), and downhill (light gray) segments.

3. Results

3.1. Performance

The general speed fluctuation patterns of Para and AB XC skiers were similar throughout the race, although Para XC skiers consistently competed at slower speed (Figures 2 and 3, Table 2). Accordingly, the female LW4 skier was 4:26 min slower compared to the female AB XC skiers across the entire race, whereas the male B3a skier was 7:21 min slower and the male B3b skier 12:47 min slower compared to the male AB XC skiers. Compared to male/female AB skiers, male/female Para skiers displayed 19/14% slower average speed with the largest time loss (65 ± 36/35 ± 6 s/lap) found in uphill terrain (Table 2). The relative speed difference between the Para and AB XC skiers was highest in uphill and flat terrain, followed by downhill terrain (Table 2).

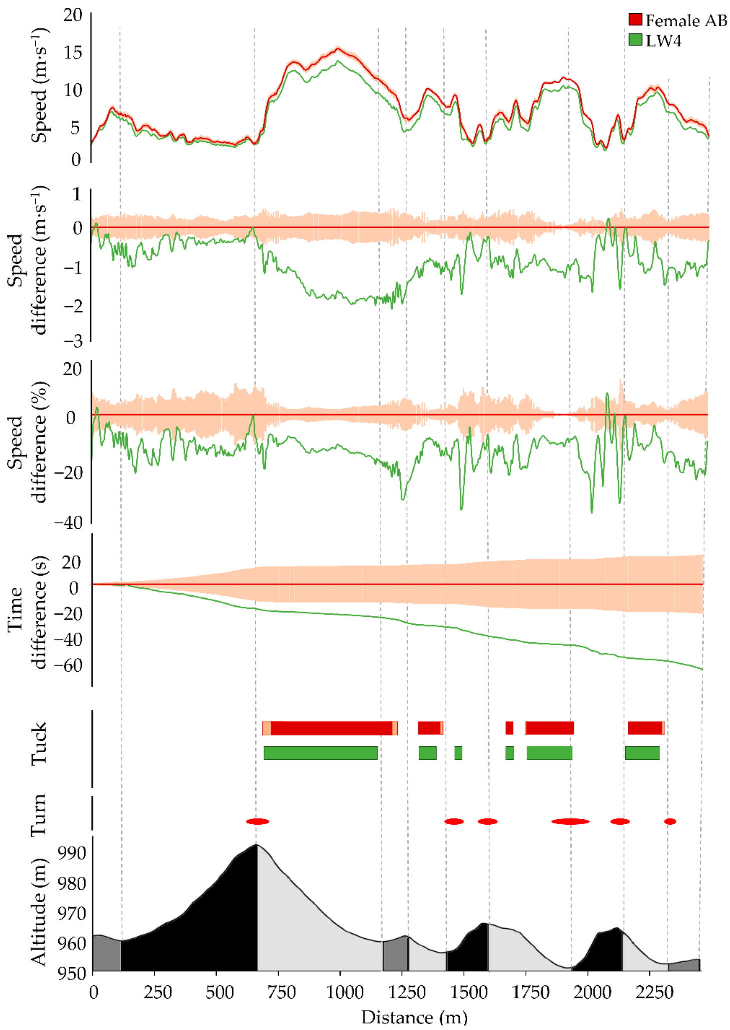


Figure 3. Comparison of average female AB XC skiers (dark red; standard deviation light pink) and female LW4 XC skier (green) for the four laps during the race with respect to average speed, absolute speed difference, relative speed difference, accumulated time difference, and tuck. Course details are visualized in the lower part of the figure; turns (red dashes) and altitude profile of the 2.5 km race course, with uphill (black), flat (dark gray), and downhill (light gray) segments.

Table 2. Proportion of skiing time in different terrain (%), absolute average speed (m·s^{-1}), relative speed difference (% of AB XC skiers), and time loss relative to AB XC skiers of same sex per lap (s) for the Para and AB XC skiers.

		LW4	Female AB	B3a	B3b	Male AB
Proportion of time in different terrain (%)	Uphill	57	58 ± 16	54	59	54 ± 14
	Flat	1.5	14 ± 1	14	14	14 ± 1
	Downhill	28	28 ± 3	31	27	32 ± 3
Absolute average speed (m·s^{-1})	Overall	6.0 ± 2.3	6.9 ± 2.6	6.7 ±	6.4 ± 2.4	7.9 ± 2.6
	Uphill	3.7 ± 0.5	4.3 ± 0.6	4.6 ± 0.6	3.9 ± 0.5	5.3 ± 0.6
	Flat	5.1 ± 0.7	6.2 ± 1.2	6.0 ± 0.6	5.7 ± 0.8	7.5 ± 1.4
	Downhill	8.3 ± 1.6	9.5 ± 1.9	8.7 ± 1.2	8.9 ± 1.5	10.3 ± 1.9
Relative speed difference (% of AB XC skiers)	Overall	14 ± 4	100	16 ± 5	20 ± 7	100
	Uphill	14 ± 2	100	14 ± 2	26 ± 3	100
	Flat	16 ± 8	100	19 ± 7	24 ± 4	100
	Downhill	12 ± 1	100	15 ± 4	14 ± 5	100
Time loss per lap (s)	Overall	65 ± 10		72 ± 7	126 ± 17	
	Uphill	35 ± 6		13 ± 11	30 ± 24	
	Flat	11 ± 3		4 ± 1	5 ± 1	
	Downhill	19 ± 2		6 ± 4	5 ± 3	

3.2. Sub-Technique Distribution

The female Para/AB XC skiers utilized on average DP, DK, DIA, and OTHER, 61/43%, 15/10%, 25/47%, and 0/0% of the distance at lower speed ranges (i.e., 2.75 to 4.75 m·s^{-1}), respectively, while the corresponding numbers for male Para/AB XC skiers were 58/18%, 1/13%, 40/69%, and 1/0%. The female Para/AB XC skiers utilized on average DP and OTHER (i.e., tuck position), 26/52% and 74/48% of the distance at higher speed ranges (i.e., 7 to 10 m·s^{-1}), respectively, while the corresponding numbers for male Para/AB XC skiers were 29/66% and 71/34% (Figures 4 and 5).

The male B3 and female LW4 XC skiers used the tuck position at similar positions during the race course as the male and female AB XC skiers (Figures 2 and 3) but employed them at a slower speed compared to the AB XC skiers (Figures 4 and 5).

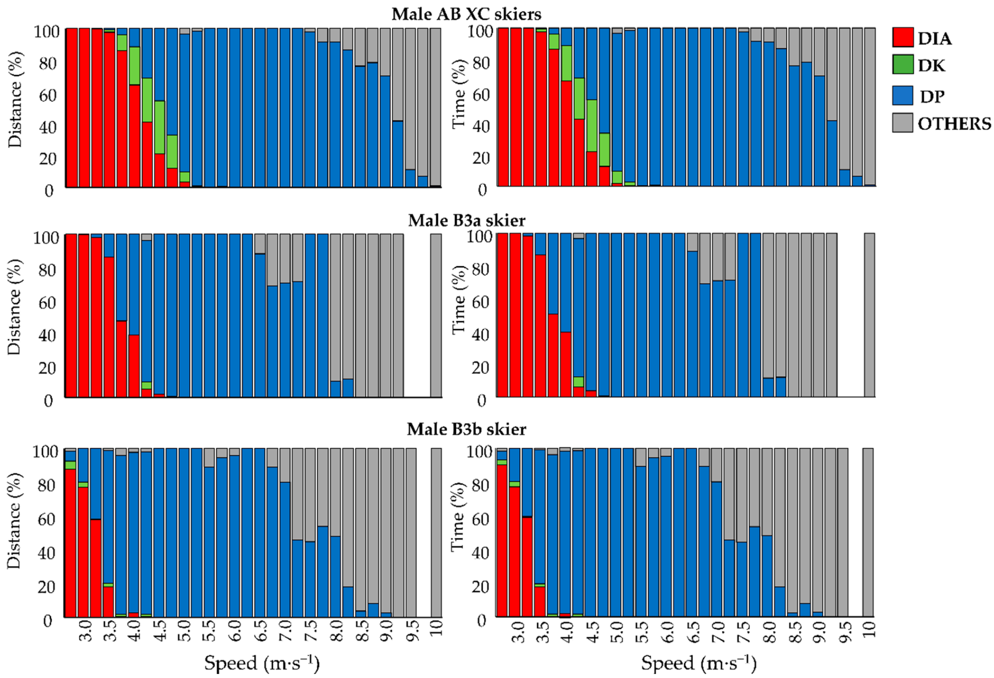


Figure 4. Distribution of sub-techniques over different speed-intervals for male AB, the B3a, and the B3b XC skiers per distance and time. Diagonal stride (DIA; red); Kick double poling (DK; green); Double poling (DP; blue); Tuck position and turn technique (OTHER; gray); White sections illustrate that the skier did not use these speeds.

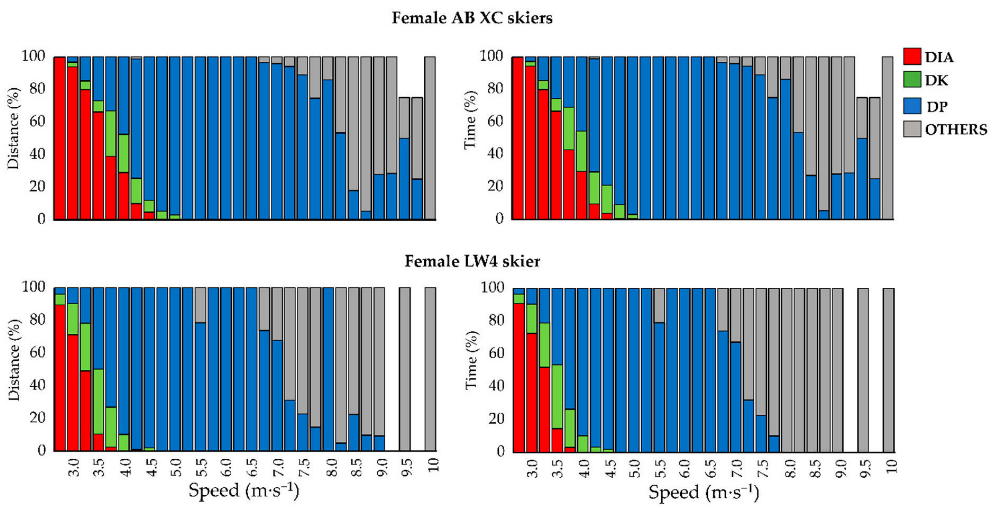


Figure 5. Distribution of sub-techniques over different speed-intervals for female AB and the LW4 XC skiers per distance and time. Diagonal stride (DIA; red); Kick double poling (DK; green); Double poling (DP; blue); Tuck position and turn technique (OTHER; gray). Blank sections for AB XC skiers and the LW4 XC skier illustrate that one of the skiers didn't used these speeds.

4. Discussion

The framework based on micro-sensor technology allowed us to descriptively compare performance and sub-technique selection between standing Para and AB XC skiers in a classical XC skiing race. Using case-series, we revealed that male/female Para skiers displayed 19/14% slower average speed with the largest time loss (65 ± 36/35 ± 6 s per lap) in uphill terrain compared to their AB counterparts. Furthermore, the Para XC skiers utilized a larger proportion of DP than DIA and DK per distance at low speeds (i.e., 2.75 to 4.75 m·s^{-1}) and a larger proportion of tuck than DP per distance at high speeds (i.e., 7 to 10 m·s^{-1}). Since we are able to distinguish clear differences between Para and AB XC skiers, we propose that the framework is feasible for future use in large-scale investigations of performance at international competitions. Especially, this is the case for more in-depth investigations on the effect of terrain and external conditions on the time factor across Para XC skiing classes.

In line with both the large speed difference and the amount of skiing time spent in uphill terrain (women: LW4: 57% and AB: 58 ± 16%; men: B3: 57 ± 3% and AB: 54 ± 14%), the time loss between the Para and AB XC skiers of the same sex were largest in this terrain. This is in accordance with previous studies in AB XC skiers who spent ~50% of skiing time in uphill terrain, in which the largest performance differences were found [4,19,24,25]. Interestingly, the relative speed difference between Para and AB XC skiers of the same sex in flat terrain was relatively similar to the difference found in uphill terrain. This differs from AB XC skiing, where the relative speed difference is less in flat compared to uphill terrain among different level skiers [19,24,25]. The large relative speed difference in flat terrain may be caused by a reduced balance and motor control of both the female LW4 [26] and the male B3 [26,27] XC skiers due to their impairments. This could have impacted the movement patterns on flat terrain at high speeds.

This is the first study to perform automatic sub-technique classification in standing Para XC skiers during an entire XC skiing race. The comparison to AB XC skiers revealed that, Para XC skiers utilized different proportions of the various sub-techniques at given low and high absolute speeds. This differs from a previous comparison between female and male AB XC skiers during a classical 10 km XC skiing race, that revealed similar proportions of used sub-techniques at same absolute speeds, despite a slower average speed employed by the female AB XC skiers [15]. Regarding the different sub-techniques between Para and AB XC skiers found here, this may be caused by the different (and possibly less technically demanding) coordination stability between arms and legs in DP compared to DIA and DK [28]. Accordingly, the greater use of DP than DIA by the Para XC skiers compared to AB XC skiers at low speeds could be speculated to be caused by the fact that DP is more suitable than DIA and DK for the Para XC skiers in the investigated speeds. In addition, the leg thrust time (i.e., the time during which the ski is in contact with the ground in a leg stride in DIA and DK) in AB XC skiing is suggested to have a speed limit that triggers the transition from DIA to DP [12,29]. For Para XC skiers such limits may be present at a lower speed. Furthermore, the Para XC skiers used a larger proportion of the distance in tuck position than DP at high speeds. Altogether, this indicates that different speed thresholds are present for the choice of classical sub-techniques in Para XC skiers than those suggested by research on AB XC skiers [6,15,17,18]. While this is likely due to disability-related limitations in the Para XC skiers, this still needs further investigation with larger sample sizes during international competitions.

Even though the proposed framework seems feasible for investigating performance also in Para XC skiers, it has some methodological limitations. The framework has only been tested in one race course and under the given external conditions. Since different external conditions (e.g., race courses with and without trees or other obstacles, weather conditions, low- vs. high-speed race courses, etc.) can affect the accuracy of the GNSS receiver, athletes who train and compete in different environments should take this into account and future studies should test the feasibility of the framework under different external conditions. Furthermore, the framework used for automatic sub-technique classification should, in future studies, be adapted for all sitting and standing Para XC skiing categories and validated in larger populations. In line with this, the framework was only applied among standing physically and visually impaired Para XC skiers in the current study, and can, therefore, only be regarded feasible in these athletes.

Practical Applications

The framework can be used to provide information on where and why Para XC skiers lose or win time compared to their competitors in a race course, as well as the effect of terrain and external conditions on the time factors used in the classification process of Para XC skiers. This could help Para XC skiers to individually define targeted training and competition strategies. In addition, our approach can be used on larger groups of Para XC skiers to provide a more detailed understanding on the influence of sub-technique and terrain on the differences between disabilities, categories, and sexes.

Furthermore, the sub-technique analyses provide information on the specific speeds and terrains where Para XC skiers employ the different sub-techniques, as well as how corresponding temporal patterns within these sub-techniques influence performance. In this study, we found a different distribution of the classical sub-techniques between the standing Para and AB XC skiers both at low and high speeds during an XC skiing race. Together with the large relative speed difference in flat terrain with high skiing speed, the movement pattern of the Para XC skiers seems to be differently exposed to the high speed than AB XC skiers, hence affecting the selected sub-technique. Such information is useful for athletes and coaches when deciding what type of training the different skiers should prioritize (e.g., improvement of technique execution and balance at high skiing speed, or development of aerobic capacity to increase performance in uphill terrain).

5. Conclusions

This study evaluated the feasibility of a framework for analyses of performance and sub-technique selection in a heterogenous group of Para XC skiers with different disabilities during a classical XC skiing race. A descriptive comparison of performance and sub-technique selection between Para and AB XC skiers indicated that the largest time loss between the Para and AB XC skiers was found in the uphill terrain. In contrast to the larger speed differences normally found in uphill terrain between performance-levels or sexes within AB skiers, the Para XC skiers displayed a similar relative speed difference compared to AB skiers in flat as in uphill terrain. This may be caused by a reduced balance and motor control of the Para XC skiers due to their impairments and also impact the movement pattern on flat terrain at high speeds. Furthermore, the Para XC skiers more frequently selected DP than DIA and DK at low speeds. Speculatively, DP could be more suitable than DIA and DK due to its lower coordinative demands for Para XC skiers who struggle with stability/coordination. Additionally, the Para XC skiers used a larger proportion of the distance in tuck position than DP at high speeds. Notably, this indicates different speed thresholds of the classical sub-techniques for Para XC skiers compared to AB XC skiers. Altogether, we hypothesize that disability impacts the selection of sub-technique among standing Para XC skiers, which could be examined by using the framework in large-scaled international investigations. Additionally, the framework opens up the possibility to investigate the effect of terrain and external conditions on the time factor across Para XC skiing classes.

Author Contributions: Conceptualization, C.H.C., J.K.B., J.K. and Ø.S.; Methodology, E.M.B.P., J.K.B. and Ø.S.; Software, J.K.; Formal Analysis, J.K., E.M.B.P. and C.H.C.; Investigation, J.K.B. and P.H.; Writing—Original Draft Preparation, C.H.C., J.K.B. and Ø.S.; Writing—Review and Editing, P.H., E.M.B.P. and J.K.; Visualization, C.H.C. and J.K. All authors have read and agreed to the published version of the manuscript.

Funding: The study was funded by the Centre for Elite Sports Research, Dept of Neuromedicine and Movement Science, Norwegian University of Science and Technology, Trondheim, Norway.

Institutional Review Board Statement: The study was approved by the Norwegian Centre for Research Data (ID 49865/3/IJJ) and conducted in line with the Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Acknowledgments: The authors would like to thank the Para and able-bodied XC skiers for their participation in the study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IPC. *Explanatory Guide to Paralympic Classification—Paralympic Winter Sports*; World Para Nordic Skiing: Bonn, Germany, 2016.
2. The International Paralympic Committee, World Para Snow Sports. Available online: https://www.paralympic.org/nordic-skiing/about (accessed on 24 February 2021).
3. IPC. *World Para Nordic Skiing Rules and Regulations Cross-Country Skiing and Biathlon*; World Para Nordic Skiing: Bonn, Germany, 2018.
4. Andersson, E.; Supej, M.; Sandbakk, Ø.; Sperlich, B.; Stöggl, T.; Holmberg, H.C. Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur. J. Appl. Physiol.* **2010**, *110*, 585–595. [CrossRef] [PubMed]
5. Losnegard, T. Energy system contribution during competitive cross-country skiing. *Eur. J. Appl. Physiol.* **2019**, *119*, 1675–1690. [CrossRef]
6. Solli, G.S.; Kocbach, J.; Seeberg, T.M.; Tjønnås, J.; Rindal, O.M.; 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*, e0207195. [CrossRef]
7. Welde, B.; Stöggl, T.L.; Mathisen, G.E.; Supej, M.; Zoppirolli, C.; Winther, A.K.; Pellegrini, B.; Holmberg, H.C. 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*, e0187111. [CrossRef]
8. 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*, 807–818. [CrossRef]
9. Stöggl, T.L.; Holmberg, H.C. Double-Poling Biomechanics of Elite Cross-country Skiers: Flat versus Uphill Terrain. *Med. Sci. Sports Exerc.* **2016**, *48*, 1580–1589. [CrossRef]
10. Göpfert, C.; Holmberg, H.C.; Stöggl, T.; Müller, E.; Lindinger, S.J. Biomechanical characteristics and speed adaptation during kick double poling on roller skis in elite cross-country skiers. *Sports Biomech.* **2013**, *12*, 154–174. [CrossRef] [PubMed]
11. 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. [CrossRef]
12. Pellegrini, B.; Zoppirolli, C.; Bortolan, L.; Holmberg, H.C.; Zamparo, P.; Schena, F. Biomechanical and energetic determinants of technique selection in classical cross-country skiing. *Hum. Mov. Sci.* **2013**, *32*, 1415–1429. [CrossRef]
13. Andersson, E.; Stöggl, T.; Pellegrini, B.; Sandbakk, Ø.; Ettema, G.; Holmberg, H.C. Biomechanical analysis of the herringbone technique as employed by elite cross-country skiers. *Scand. J. Med. Sci. Sports* **2014**, *24*, 542–552. [CrossRef] [PubMed]
14. Bucher Sandbakk, S.; Supej, M.; Sandbakk, Ø.; Holmberg, H.C. Downhill turn techniques and associated physical characteristics in cross-country skiers. *Scand. J. Med. Sci. Sports* **2014**, *24*, 708–716. [CrossRef] [PubMed]
15. 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*, e0239862. [CrossRef]
16. Ettema, G.; Kveli, E.; Øksnes, M.; Sandbakk, Ø. The role of speed and incline in the spontaneous choice of technique in classical roller-skiing. *Hum. Mov. Sci.* **2017**, *55*, 100–107. [CrossRef]
17. Marsland, F.; Anson, J.; Waddington, G.; Holmberg, H.C.; Chapman, D.W. Macro-Kinematic Differences Between Sprint and Distance Cross-Country Skiing Competitions Using the Classical Technique. *Front. Physiol.* **2018**, *9*, 570. [CrossRef] [PubMed]
18. Marsland, F.; Mackintosh, C.; Holmberg, H.C.; Anson, J.; Waddington, G.; Lyons, K.; Chapman, D. Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition. *PLoS ONE* **2017**, *12*, e0182262. [CrossRef]
19. Sandbakk, Ø.; Losnegard, T.; Skattebo, Ø.; Hegge, A.M.; 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. [CrossRef]
20. Sollie, O.; Gløersen, Ø.; Gilgien, M.; Losnegard, T. Differences in pacing pattern and sub-technique selection between young and adult competitive cross-country skiers. *Scand. J. Med. Sci. Sports* **2021**, *31*, 553–563. [CrossRef]
21. Seeberg, T.M.; Tjønnås, J.; Rindal, O.M.; Haugnes, P.; Dalgard, S.; Sandbakk, Ø. A multi-sensor system for automatic analysis of classical cross-country skiing techniques. *Sports Eng.* **2017**, *20*, 313–327. [CrossRef]
22. 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. [CrossRef]
23. Rindal, O.M.; Seeberg, T.M.; Tjønnås, J.; Haugnes, P.; Sandbakk, Ø. Automatic Classification of Sub-Techniques in Classical Cross-Country Skiing Using a Machine Learning Algorithm on Micro-Sensor Data. *Sensors* **2017**, *18*, 75. [CrossRef] [PubMed]
24. Bolger, C.M.; Kocbach, J.; Hegge, A.M.; Sandbakk, Ø. Speed and heart-rate profiles in skating and classical cross-country skiing competitions. *Int. J. Sports Physiol. Perform* **2015**, *10*, 873–880. [CrossRef] [PubMed]

25. Sandbakk, Ø.; Ettema, G.; Leirdal, S.; Jakobsen, V.; Holmberg, H.C. Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur. J. Appl. Physiol.* **2011**, *111*, 947–957. [CrossRef] [PubMed]
26. Norges Skiforbund. Available online: https://www.skiforbundet.no/langrenn (accessed on 12 February 2021).
27. Klavina, A.; Jekabsone, I. Static Balance of Persons with Intellectual Disabilities, Visual Impairments and without Disabilities. *Eur. J. Adapt. Phys. Act.* **2014**, *7*, 50–57. [CrossRef]
28. Cignetti, F.; Schena, F.; Zanone, P.G.; Rouard, A. Dynamics of coordination in cross-country skiing. *Hum. Mov. Sci.* **2009**, *28*, 204–217. [CrossRef]
29. Nilsson, J.; Tveit, P.; Eikrehagen, O. Effects of Speed on Temporal Patterns in Classical Style and Freestyle Cross-Country Skiing. *Sports Biomech.* **2004**, *3*, 85–107. [CrossRef]

STUDY III

This paper is not included due to copyright
available in
International Journal of Sports Physiology and Performance (IJSPP) 2021 ;Volum 16.(11) s. 1596-1602
https://doi.org/10.1123/ijspp.2020-0752

ISBN 978-82-326-6343-9 (printed ver.)
ISBN 978-82-326-5453-6 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

NTNU
Norwegian University of
Science and Technology