Doctoral thesis

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by

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Philosophiae Doctor

Oslo, May 2023

Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science
Centre for Elite Sports Research

Avhandlingens tittel på norsk:

Analyse av prestasjon, fysiologiske responser og bevegelsesteknikk i langrenn ved bruk av sensor data

Populærvitenskapelig sammendrag:

Hovedmålet med denne doktorgradsavhandlingen var å undersøke fysiologiske respons og bevegelsesteknikk i variert terreng under ulike treningsintensiteter og i forbindelse med fellesstart-konkurranser i langrenn. Alle studiene er gjennomført i stilarten skøyting med målinger fra bærbare sensorer, som avslutningsvis ble benyttet i kombinasjon med video og fotoceller med mål om å forbedre den teknisk-taktiske gjennomføringen av en langrenns konkurranse.

Først ble det gjennomført to studier på rulleski i et innendørs, kontrollert laboratoriemiljø på tredemølle. Her ble bærbare sensorer kombinert med laboratoriemålinger for å undersøke forskjeller i ulike fysiologiske responser og bevegelsesteknikk mellom trening på lav og høy intensitet. Deretter ble betydningen av ulike prestasjonsbestemmende faktorer i en simulert fellesstart undersøkt. Ved å inkludere bærbare sensorer og «gullstandardmetoder» samtidig fikk vi bedre grunnlag for å tolke dataene vi senere samlet utendørs i to oppfølgingsstudier: en studie som undersøkte løpsutvikling og prestasjonsbestemmende faktorer under en offisiell fellesstart-konkurranse regulert av det internasjonale ski- og snøbrettforbundet (FIS), og en intervensjonsstudie der vi undersøkte effekten av video- og sensorbasert feedback for å optimalisere prestasjonen over bakketoppene under to testrenn i intervallstart.

Det første studiet ble inspirert av at elite langrennsløpere, som til tross for høy konkurranseintensitet, gjennomfører stordelen av treningen på lav intensitet. Hovedfunnene fra dette studiet viste at langrennsløpere stort sett benytter samme delteknikk, frekvens og kraftfordeling mellom armer og ben både på lav og høy intensitet, spesielt i mindre krevende terreng. I tillegg hadde de tilsvarende fluktuasjon i fysiologisk respons som funksjon av terrenget på begge intensiteter. Disse funnene indikerer at viktige konkurranseegenskaper også kan trenes effektivt ved lav intensitet.

Våre to studier på fellesstart viste at denne konkurranseformen har mange fellestrekk med individuell start, som at god aerob utholdenhet og effektivitet korrelerer med bedre prestasjon, og at oppoverbakker er det mest avgjørende terrengpartiet for resultatene. De beste løperne klarer også å bruke mer krevende delteknikker og teknisk utførelse i bratte bakker. Samtidig var det en viktig forskjell: løpere med høyt maksimalt oksygenopptak og god effektivitet kunne spare energi for å bruke den mer effektivt i sluttfasen og i spurten av en fellesstart, i stedet for å benytte disse egenskapene til å gå jevnt raskere gjennom hele løpet slik en ser i intervallstarter. Forskningen vår avdekket også viktigheten av gruppedynamikk i fellesstart, der løperne danner dynamiske grupper for å redusere luftmotstanden, og de fleste prøver å følge teten så lenge de kan for å dra nytte av dette. I store felt dannes det også en trekkspilleffekt som gjør at de som ligger bak bruker unødvendig mye krefter på akselerasjoner og retardasjoner, i tillegg til at dette gir høyere risiko for uhell. Samtidig vil de beste ha krefter til være med på rykk underveis og ha en god spurt mot slutten.

I vår siste studie fant vi ut at presise tilbakemeldinger basert på sensor data og video, kombinert med spesifikk trening i løypene, under forberedelsene til en konkurranse bidro til forbedret prestasjon i lett-terreng. Intervensjonsgruppen viste endret adferd og oppnådde høyere total akselerasjon over den spesifiserte bakketoppen de fikk tilbakemelding på. Dette resulterte i tidsbesparelse sammenlignet med kontrollgruppen i den etterfølgende nedoverbakken og tilsvarende terrengpartier i andre deler av løypa.

Samlet sett gir studiene presentert i denne avhandlingen ny innsikt i de fysiologiske og biomekaniske faktorene som ligger til grunn for langrennsprestasjoner, inkludert betydningen av løpsstrategi, gruppedynamikk, teknikk og andre prestasjonsbestemmende faktorer i fellesstart konkurranser i langrenn. Gjennom bruk av sensorer, kombinert med tilpasset signalbehandling og intelligent klassifisering, kan vi tilegne oss ny og verdifull innsikt i arbeidskravene i langrenn. Denne teknologien kan dessuten brukes direkte under trening for å heve kvaliteten.

Navn kandidat: Trine M. Seeberg
Hovedveileder: Øyvind B. Sandbakk
Medveiledere: Jan Kocbach og Johannes Tjønnås

Finansieringskilde:

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Ovennevnte avhandling er funnet verdig til å forsvares offentlig for graden PhD ved NTNU - Fakultet for medisin og helsevitenskap - Institutt for nevromedisin og bevegelsesvitenskap. Disputas finner sted i Toppidrettssenteret i Granåsen 17 oktober kl.12.15.

Summary

The main objective of this thesis was to investigate physiological responses, movement techniques, and their associations with training intensity and performance in cross-country skiing (XC) using sensor data, with a particular emphasis on mass-start competitions and the skating technique. The thesis followed a sequential approach, starting with two indoor studies conducted under standardized conditions. In these studies (Paper 1 and Paper 2), wearable sensors were used in conjunction with standard laboratory measurements to establish a foundation for interpreting data collected from sensors in outdoor settings. This approach allowed for the integration of highly accurate reference sensors and methodology, contributing to the development of expertise in analyzing outdoor sensor data.

Subsequently, two outdoor studies were conducted: one during an official mass-start competition (Paper 3) and one intervention study involving two time trials (Paper 4). The overall structure of the thesis is outlined in **Figure 1,** and the rationale and key findings of each study are described below.

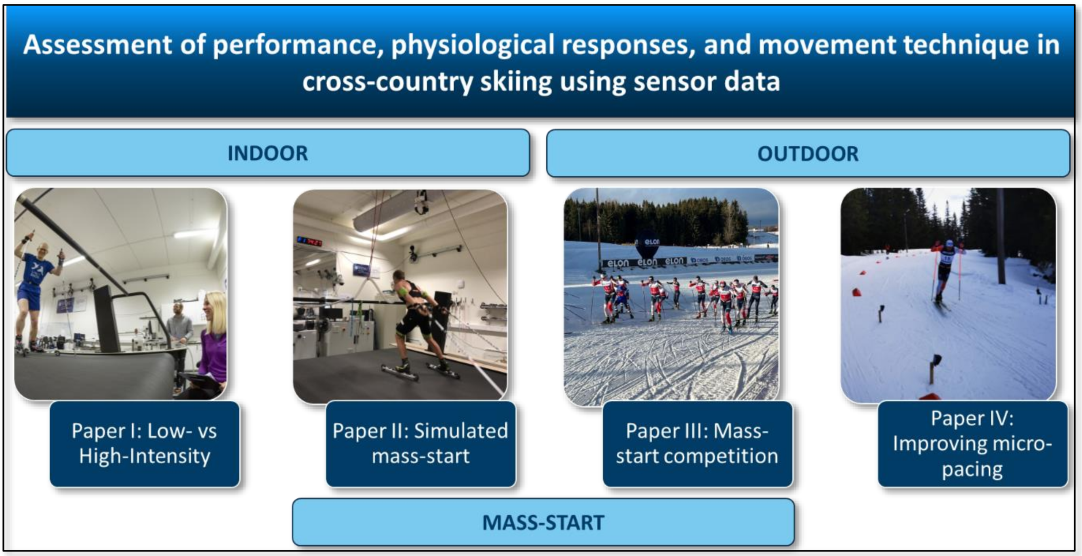

Figure 1 Outline of the PhD thesis "Assessment of performance, physiological responses, and movement technique in cross-country skiing using sensor data". Photo: NTNU

The impact of training intensity on physiological and biomechanical factors - Competitive XC skiing is a physiologically and technically demanding endurance sport in which speed, work rate, and energy expenditure fluctuate with the constantly changing terrain. However, despite XC skiing competitions being performed at high-intensity and high-intensity sessions being considered crucial for the development of XC skiers, the majority of training time is spent on low-intensity sessions. The specific physiological and biomechanical stimulus provided during low-intensity training, and

its similarities with competition-specific demands, have not been adequately explored. Therefore, an indoor study was conducted under controlled environments to investigate the similarities and differences in the physiological and biomechanical responses to low- and high-intensity roller ski skating on varying terrain (Paper 1). Several similarities between low- and high-intensity training on varying terrain were observed. Both low- and high-intensity training induced significant terrain-dependent fluctuations in heart rate, oxygen uptake, and muscle oxygen saturation. Furthermore, the power distribution generated by poles and skis showed a similar pattern for both low- and high-intensity, with a time-dependent shift towards increased power from the ski push-off from the start to the end of each session within all sub-techniques. Terrain-based fluctuations in oxygen uptake were also similar at both intensities. However, there were also differences between the two intensities. Heart rate exhibited less fluctuation at high- intensity and demonstrated a time-dependent increase known as cardiovascular drift. Additionally, gear 2 sub-technique was employed more frequently than gear 3 on the steepest uphill section during low- intensity compared to high-intensity, while cycle length increased 2–3 times more than cycle rate, and contact time for poles decreased more than contact time for skis when transitioning from low to high- intensity in the same terrain. The findings suggest that many of the demands that are important for XC skiing competitions can be adequately stimulated during low-intensity training, especially in less strenuous terrain. This may partially explain the benefits of low-intensity training, as it allows for a high volume of training while minimizing the accumulation of fatigue.

Mass-start events: an unexplored racing format in XC skiing - Different competition formats in XC skiing vary in distance, style (i.e., classic and/or skating), and type of starting procedure (i.e., individual time trials or mass-starts). Therefore, the impact of associated performance-determining factors can also differ considerably. Despite being the most common race format in XC skiing, mass-start events have not been scientifically examined. Hence, we conducted two studies focusing on mass-start events: one describing race development and performance-determining factors in a mass-start XC skiing competition (Paper 3) and one exploring physiological and biomechanical responses to a simulated mass-start race on a treadmill (Paper 2).

In Paper 2, it was found that mass-start competitions were influenced by many of the same performance-determining factors as individual time trials. Higher maximal oxygen uptake and gross efficiency were associated with better mass-performance, and uphill performance was identified as the most differentiating terrain. The top skiers utilized skiing sub-techniques suitable for higher speeds and adjusted the associated macro parameters accordingly in steep terrain. However, a novelty of this study was that higher maximal oxygen uptake and gross efficiency capacities appeared to have a different impact on mass-starts compared to time trials. Rather than using superior capacities to ski faster than lower-level peers throughout the entire race, as typically observed in time trials, our findings suggest that skiers with high scores in these performance-determining variables could conserve energy and “utilize” their reserves better towards the end of the race and during the final sprint.

In Paper 3, we further revealed the importance of group dynamics and related factors in mass-start events. It was observed that skiers formed dynamic packs to benefit from drafting, and the majority of participants adopted the strategy of following the leader for as long as possible. This resulted in a more positive pacing pattern for lower-performing skiers, which may not have been optimal for their performance. The presence of a significant accordion effect in the first half of the competition led to additional decelerations, accelerations, and a higher risk of incidents that disadvantaged skiers positioned at the back of the pack. In summary, the key factors determining mass-start performance were found to be an adequate starting position (based on performance level), the ability to avoid incidents and disadvantages caused by the accordion effect, tolerance for intensity fluctuations, maintaining speed throughout the competition, and possessing well-developed final sprint abilities.

The performance impact of optimizing micro-pacing strategies - An essential factor in endurance competitions is optimizing the pacing strategy, which involves utilizing energetic resources as effectively as possible from start to finish. In XC skiing, skiers naturally employ a variable pacing pattern with higher metabolic rates and power production during uphill sections compared to flat and downhill terrain. Therefore, refining XC skiers micro-pacing strategy by adjusting speed and transitions between sub-techniques within or between terrain sections can be beneficial for performance improvement. Based on practical training with world-class skiers and findings in the literature, it was hypothesized that increasing speed over specific hilltops to save time in subsequent downhill sections, without reducing speed in other parts of the track, could enhance XC skiing performance. It was also hypothesized that this skill could be learned in a short-term competition-preparation setting.

The intervention conducted in Paper 4 aimed to investigate the performance effects of video- and sensor-based feedback for implementing a terrain-specific micro-pacing strategy in preparation for an XC skiing competition. The results demonstrated that the intervention group significantly reduced the time spent in the targeted downhill segment and overall downhill and flat terrain, compared to matched controls who underwent similar training without any instructions or feedback. No significant effects of the intervention were observed in physiological responses, time spent in uphill terrain, or overall race performance. In conclusion, targeted training combined with video- and sensor-based feedback has the potential to successfully improve terrain-specific micro-pacing strategies in XC skiing.

Utilizing sensors in outdoor XC skiing - In relation to this thesis, the performance, physiological responses, and movement technique of national-level skiers were explored using multiple wearable sensors during training and competition. Global Navigation Satellite Systems (GNSS) sensors were employed to measure speed and position, providing a valuable tool for tracking performance and measuring speed profiles both in training and competition. Inertial Measurement Units (IMUs) were used to validly classify skate sub-techniques and assess the corresponding macro- and micro-parameters, both indoors and outdoors. IMUs also enabled the estimation of total variation of chest acceleration, which serves as a measure of biomechanical intensity. The exploration of physiological measurements presented several challenges. Simultaneous measurements of oxygen uptake ($\dot{V}O_2$) and heart rate (HR) revealed that HR exhibited intensity-dependent drift and asymmetrical responses to terrain, which differed from the $\dot{V}O_2$ response. Therefore, caution must be exercised when interpreting HR measurements as a surrogate for $\dot{V}O_2$ in fluctuating terrain. Similar caution applies to near-infrared spectroscopy (NIRS) measurements, used to track variations in muscle oxygenation based on terrain and sub-techniques, as there is a significant individual variability that disqualifies its use as an absolute measure. In addition, this approach challenged the practical problem of measuring all parameters at the same time and successfully synchronizing them to a common timeline, which is required to provide complementary and integrative understanding. Lastly, Paper 4 demonstrated that sensor data can be utilized to drive behavioral changes. The methodology employed in this study is likely generalizable and transferable to other settings, offering an effective learning process to improve technical or tactical skills in various sports or during rehabilitation.

Taken together, the studies presented in this thesis provide novel insights into the physiological and biomechanical factors that underpin XC skiing performance. They highlight the significance of pacing strategy, group dynamics, technique, and other performance-determining factors in mass-start competitions. The utilization of various sensor data, along with customized signal processing and intelligent classification and detection models, provides valuable new insights into the interconnected physiological and biomechanical demands of XC skiing. Moreover, these findings can be directly applied during training to enhance the quality of each session and effectively improve technical and tactical skills.

Acknowledgments

This PhD thesis was conducted at the Centre for Elite Sports Research, Department of Neuromedicine and Movement Science, within the Faculty of Medicine and Health Sciences at the Norwegian University of Science and Technology in Trondheim. Concurrently, I worked part-time as a Senior Scientist at SINTEF AS, SINTEF Digital, Department for Smart Sensors and Microsystems in Oslo until December 2021. From January 2022 onward, I served as the Chief Scientific Officer and co-founder of Aidee Health AS. Thank you to both SINTEF and Aidee Health AS for the possibility of conducting this thesis.

Then, thanks to the Norwegian Research Council for funding the AutoActive project, which included this PhD thesis. Thanks to the whole AutoActive-team for a fruitful collaboration and project; Andreas and Frederic from UiO, Elisabeth and Pål from OUS, Stine Marit, Thomas and other contributors from MS Senteret, Øyvind, Jan and the rest from NTNU SenTIF and Olympiatoppen, Anders, Victor, Sigurd, Kasper, Steffen, Ole Marius and other contributors from SINTEF. I think we did an outstanding job with this project with major contributions to science in different areas!

Generally, I would like to thank all the skiers participating in the data collections for their hard effort, and all others that facilitated the studies. I also would like to thank my many co-authors for their contribution to the different studies. Thanks to all my highly skilled colleagues at SenTIF that have been co-authors and parts of the different studies or discussions; Guro, Dionne, Rune, Pål, Knut, Jørgen, Roy, Gertian, Julia and Marius. A special thanks to Guro that also were the last author of Paper 4, who has been a big inspiration for me due to her impressive research in combination with her skills as an athlete and coach, and her humble and hard-working personality. An extra thanks to Pål, that collected some of the indoor data that was used for the model for sub-technique detection and manually labeled a lot of the data that was collected outdoors. I know it was a lot of work and I really appreciate it! Also, a big thanks to Evy, Emma and Tore that helped with data collections, and to Hanna who wrote her master thesis on the mass-start. And thanks to the whole Meråker team, Nord University, Meråker Videregående and the many other people involved, that we managed to execute that extensive data collection during the pandemic was really impressing. Thanks to Thomas at Olympiatoppen and NIH for contributing as co-author in Paper 4, I really enjoyed working with you.

Thanks to all my colleagues at SINTEF and especially all members of my group at SINTEF, Health and Performance technology. A special thanks to Johannes, that also has been my co-supervisor. Your software skills, work-moral, patience related to small issues and eye for detail are impressive.

Thanks to Ingrid for reading and reviewing my thesis, for cheering for me and for making our group at SINTEF the most fun place to work. Thanks to Mats that let me do this thesis along with my other work at SINTEF, and to Ingeborg for always facilitating my work at SINTEF with a smile and to Elin for being my work-friend, helping me with all different stuff in SINTEF and for being you.

Also, thanks to my co-founders at Aidee Health AS, who have patiently “allowed me" the time to finish my PhD work within a reasonable timeframe. Thanks to all my friends, the ladies in “Strømmen-gjengen”, and “Syklubben” (girlfriends from NTNU physics) and “Team LettOgFin” for always supporting and cheering for me.

Then my two superheroes deserve a special thank:
To my main supervisor Øyvind B. Sandbakk. Øyvind, if supervising was a part of a championship, you would have won the gold medal. From start to finish you have been present with an inexhaustible commitment. You have challenged me but at the same time provided the necessary support and autonomy to keep my motivation high throughout this thesis. Your leadership and ability to develop and support the people around you are of great inspiration to me. You have also become a dear friend, and I am really going to miss our regular meetings with interesting and fruitful discussions.

To my co-supervisor Jan Kocbach: Thanks for all your help and support, your eyes for the small things and to challenging me to reach perfection. This thesis had not been possible without your skills and drive for doing more. Also, your work capacity and work-life balance have been and still is a big inspiration for me. I will really miss our regular meetings and discussions.

And lastly, thanks to my family, Håvard, and my three kids, Simen, Sara and Sofie, for challenging me in all ways and forcing me to be "present" and to invest time in other stuff than work. Thanks to Håvard for never complaining even though my work keeps getting in the way for everything. Thanks to Simen for inspiration, fruitful discussions related to XC skiing and training physiology and for participating in the study, thanks to Sara for always being helpful with everything and for bringing sunshine into our family. Lastly, thanks to Sofie, who has grown up alongside this thesis and my other work commitments. I know that you are fed up, but your resilience and patience have been remarkable, my tough girl!

Now this journey has come to an end, and it is time to return to my “day-job”. I really enjoyed every step of the way.

Preface

This PhD has been conducted as part of the research project "Tools and Methods for Autonomous Analysis of Human Activities from Wearable Device Sensor Data" (short name AutoActive), funded by the Norwegian Research Council in the IKT Pluss program (project number 270791)[1]. The AutoActive project was conducted in the time period 2018-2022.

The primary objective of AutoActive was to realize tools, methods and algorithms that allow extraction of reliable and useful information on human activity from heterogeneous sensor data. A requirement for the developed tools was that they should enable support of current and future research projects and development in a wide range of applications.

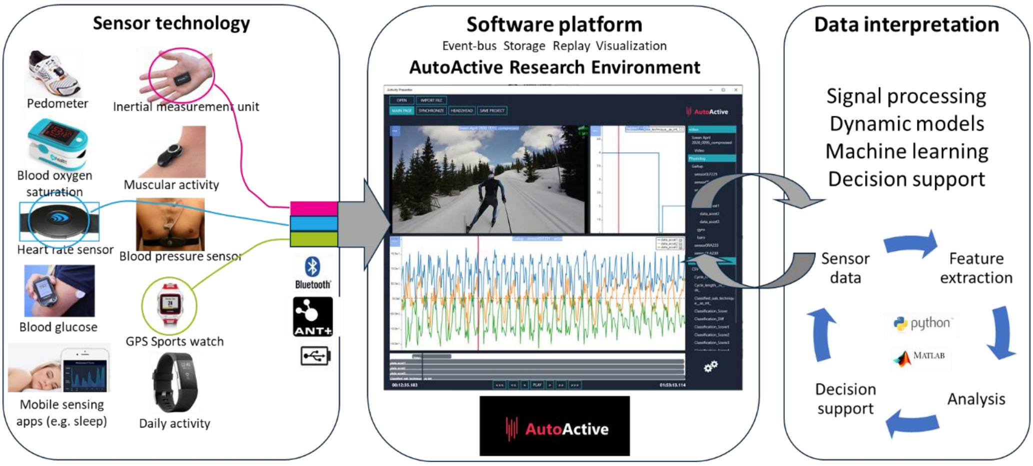

Figure 2 Illustration of feasibility of the AutoActive research environment (Albrektsen, 2021).

To test and validate the developed tools, two specific user cases were chosen: 1) Exercise Performance (with a special focus on XC skiing) and 2) Disease management (with a special focus on persons with multiple sclerosis).

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[1] https://prosjektbanken.forskningsradet.no/en/project/FORISS/270791?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&TemaEmne.2=Klinisk+forskning&Fritekst=+270791

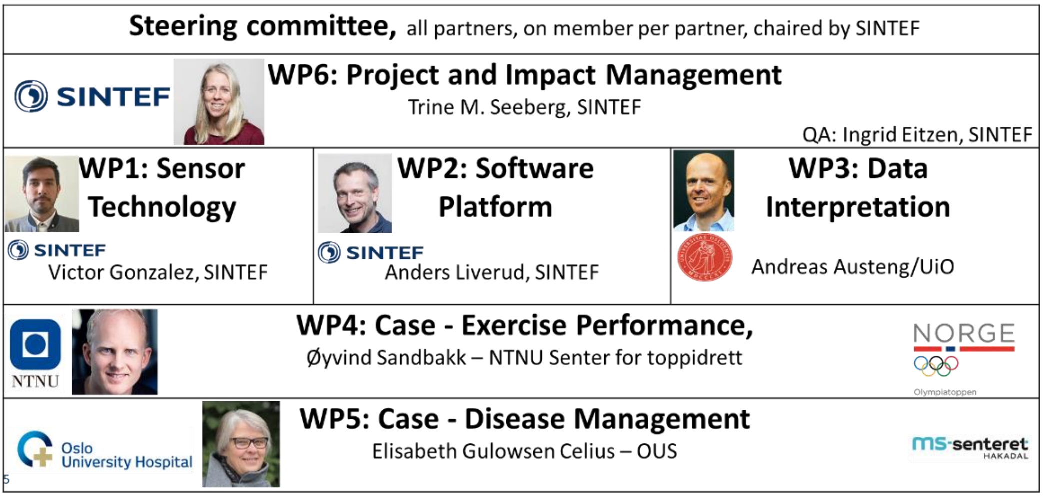


Figure 3 The management structure and work package (WP) distribution in AutoActive project. Of note, the PhD candidate submitting the current thesis was project leader of the entire project and wrote her PhD thesis in WP4.

The project was led by SINTEF Digital, (the project leader have been the PhD candidate of this thesis Trine M. Seeberg) and consisted of a multidisciplinary consortium with the following project partners covering both technical and domain expertise: 1) Technical competence; SINTEF Digital - Smart Sensor Systems and Mathematics and Cybernetics (sensor technology, biomedical instrumentation, software engineering, internet of things) and the University of Oslo - Digital Signal Processing and Image Analysis (machine learning, signal processing), and 2) partners with domain competence; NTNU Centre for Elite Sports Research (elite sport), Olympiatoppen (elite sport), Oslo University Hospital - Department of Neurology (multiple sclerosis) and MS Senteret Hakadal (multiple sclerosis). The management structure and work package distribution are visualized in **Figure 3**.

This PhD position was linked to WP4 and the use case 1) Exercise Performance.

List of papers

This thesis is based on the following original research papers:

Paper 1 - Seeberg, T. M., Kocbach, J., Danielsen, J., Noordhof, D. A., Skovereng, K., Meyer, F., & Sandbakk, Ø. (2021). **Physiological and Biomechanical Responses to Cross-Country Skiing in Varying Terrain: Low- vs. High-Intensity**. Frontiers in Physiology, 12. https://doi.org/10.3389/fphys.2021.741573

Paper 2 - Seeberg, T. M., Kocbach, J., Danielsen, J., Noordhof, D. A., Skovereng, K., Haugnes, P., Tjønnås, J., & Sandbakk, Ø. (2021). **Physiological and Biomechanical Determinants of Sprint Ability Following Variable Intensity Exercise When Roller Ski Skating**. Frontiers in Physiology, 12, 638499. https://doi.org/10.3389/fphys.2021.638499

Paper 3 - Seeberg TM, Kocbach J, Wolf H, Talsnes RK, Sandbakk ØB. (2023) **Race development and performance-determining factors in a mass-start cross-country skiing competition.** Front Sports Act Living. https://doi.org/10.3389/fspor.2022.1094254.

Paper 4 - Seeberg TM, Kocbach J, Kjøsen Talsnes R, Meyer F, Losnegard T, Tjønnås J, Sandbakk Ø, Solli GS. **Performance Effects of Video- and Sensor-Based Feedback for Implementing a Terrain-Specific Micropacing Strategy in Cross-Country Skiing.** Int J Sports Physiol Perform. 2022 Oct 21;17(12):1672-1682. https://doi.org/10.1123/ijspp.2022-0106.

Abbreviations

BLa	Blood lactate concentration
CL	Cycle Length
CR	Cycle Rate
CT_{pole}	Contact time pole
CT_{ski}	Contact time ski
DIA	Diagonal Stride
DK	Double Poling with a Kick
DP	Double Poling
FIS	International Ski and Snowboard Federation
G2	Gear 2 sub-technique
G3	Gear 3 sub-technique
G4	Gear 4 sub-technique
G5	Gear 5 sub-technique
GPS	Global Positioning System
GNSS	Global Navigation Satellite Systems
HI	High-Intensity
HR	Heart Rate
HR_{max}	Maximal Heart Rate
$\%HR_{max}$	Relative HR in %-age of HR_{max}
IMU	Inertial Measurement Unit
LI	Low-Intensity
NIRS	Near infrared spectroscopy
Other	Other sub-techniques including tucking and turning
$\%P_{ski}$	Power from lower body (skis)
$\%P_{pole}$	Power from upper body (poles)
RPE	Rate of perceived exertion
totVarAcc	Total variation of chest acceleration on hilltop (i.e., a metric for biomechanical intensity)
TSI	Tissue Saturation Index
TSI_{leg}	TSI measured by the sensor placed on the vastus lateralis in the right leg.
TSI_{arm}	TSI measured by the sensor placed on the long head of the triceps brachii in the right arm.
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake reached in a given exercise mode or test protocol
$\%\dot{V}O_{2max}$	Relative $\dot{V}O_2$ in %-age of $\dot{V}O_{2max}$
XC	Cross-Country

Table of Contents

1 Background

1.1 The rationale for the thesis

Performance, physiological responses, and movement techniques have been studied in the indoor laboratory during stable conditions in many types of sport and can in those conditions be relatively well measured and interpreted (Pellegrini et al., 2021). These environments allow us to monitor and visually observe the athletes continuously, as well as using gold standard laboratory equipment and methods in standardized conditions. However, these methods also have their limitations. The laboratory facilities and equipment required can be costly, and the methods often involve time-consuming manual notational analysis, which is susceptible to human errors and biases. In addition, in sports where the athletes train and compete outdoors during varying weather conditions, terrains and grounds, laboratory measurements cannot validly simulate these conditions (Verheul et al., 2020).

To the contrary, measuring performance outdoors during real-time field conditions can in many sports be difficult due to several reasons: 1) laboratory equipment is often not movable or robust enough, 2) the performance is highly dependent on the weather conditions, equipment, terrain and surface, 3) gold standard measurement methods for performance are often challenging to apply and 4) it is impractical and often not possible to visually monitor the athletes who move fast across large areas. For most outdoor sports, more research is needed to develop and utilize methods and technology that are feasible for monitoring athlete performance, physiological response and technique during training and competition in field conditions (Li et al., 2016; Verheul et al., 2020; Pellegrini et al., 2021). Cross-country (XC) skiing is one of the outdoor sports where knowledge of these aspects has been sparse. Due to the unique complexity and requirements of XC skiing, this sport was chosen as the movement form in our research model for this thesis. In addition, there is limited knowledge on the most used competition-format in XC skiing; the mass-start events.

The possibilities for performance analysis methods in sports science are rapidly accelerating, primarily due to improved technology and applications from computer science (Araújo et al., 2021). The increasing availability of wearable sensors has given us new and important insight into the demand of the XC skiing competitions and the physiological, tactical, and technical demands of the XC skiers (Stöggl et al., 2014; Marsland et al., 2017; Rindal et al., 2017; Seeberg et al., 2017; Marsland et al., 2018; Solli et al., 2018; Tjønnås et al., 2019). Still, automatic movement recognition and rating of technique using data from wearable sensors both for XC skiing and other sports, applicable both in lab and during outdoor conditions, has a considerable potential to further enhance performance analysis. Notably, valid methods based on sensor data can facilitate more efficient and accurate study design and analysis (Araújo et al., 2021).

Therefore, the main objective of this PhD was to investigate physiological responses and movement technique and their associations with training intensity and performance in XC skiing, with a particular emphasis on mass-start competitions and the skating technique. Thereby, this thesis aimed to enable development of analysis methodology applicable to indoor lab-tests, outdoor studies, training, and competition sessions. Being able to use objective sensor data to provide an integrated understanding of performance parameters, physiological responses, and movement technique, as well as their interrelations, in this complex sport, would provide a significant contribution to sport science. By managing the complex technical challenges in XC skiing, this knowledge should also be transferable to other sports or during rehabilitation. Skating style was chosen instead of classical style since it is more widely used (XC skiing, biathlon, Nordic combined, and XC skiing orienteering) and is the preferred exercise XC technique in central Europe. In addition, many of the challenges solved in classic has not yet been done in skating – highlighting a potential to gain new and relevant knowledge.

1.2 The fundamentals of XC skiing

XC skiing is a physiologically and technically demanding endurance sport performed outdoors in cold conditions (Sandbakk and Holmberg, 2017). The international XC skiing race program consist of competitions with a variation in distance (from sprint distances of ~1.5 km with racing time of less than 2 minutes to 50 km distances with racing time of 2 hours) and start procedures (sprint, individual time trials and mass-starts) performed in special racecourses (International Ski and Snowboard Federation (FIS), 2022). The competitions are performed in one of the two styles (or a combination) with corresponding sub-techniques, classical (diagonal stride (DIA), double poling with a kick (DPK), double poling (DP) and herringbone) or skate (gear 2 (G2), gear 3 (G3), gear 4 (G4) and gear 5 (G5)). In addition, the downhill tuck position and a variety of turn techniques are employed within both styles (**Figure 4**).

Since the racecourses in XC skiing consist of approximately one-third ascending, one-third flat and one-third descending terrain (International Ski and Snowboard Federation (FIS), 2022) and the courses are designed so that each segment is short and typically lasts for less than a minute (Losnegard, 2019), there is a substantial fluctuation in speed, work rate, and energy expenditure with the changing terrain. Accordingly, successful XC skiing requires to ski efficiently within the different sub-techniques (Sandbakk and Holmberg, 2017), meaning that the XC skiers must frequently shift between the various sub-techniques with varying contributions from leg and arm work and adapt macro parameters, i.e., cycle rate (CR) and cycle length (CL) and micro-parameters (i.e., for example contact time and swing time for poles and skis) according to the track topography (Holmberg, 2015; Sandbakk and Holmberg, 2017). The technique chosen is influenced by speed and external conditions (such as the profile of the terrain, snow conditions, waxing of skis and altitude), as well as individual performance level and physical characteristics. In both the skating and classical techniques, attaining higher speed requires both the production of sufficient propulsive force to increase cycle length, as well as more rapid cycles (Solli et al., 2018). Longer cycle length is particularly important at high speeds on flat terrain, whereas rapid cycles while minimizing the reduction in cycle length is mandatory for accelerating on steep hills, during the start and sprinting at the finish of races. To accomplish this, more explosive techniques, such as “running diagonal” and “kangaroo double poling” have been developed (Holmberg et al., 2005; Lindinger et al., 2009b; Stöggl et al., 2010). In addition, there is increasing focus on the downhill sections of a race, especially the challenging downhill turns, where faster skiers utilize the accelerating step-turn technique more extensively (Sandbakk et al., 2014).

Generally, according to a physiological model (Joyner and Coyle, 2008), three main physiological and biomechanical factors play key roles in endurance performance, i.e., maximal oxygen uptake ($\dot{V}O_{2max}$), the lactate threshold (an indicator of the highest fraction of $\dot{V}O_{2max}$ the athlete can work without accumulating fatigue) and, finally, the efficiency (i.e. the oxygen cost to generate a given speed or power output) (Joyner and Coyle, 2008). In this model $\dot{V}O_{2max}$ and lactate threshold interact to determine the ‘performance $\dot{V}O_2$‘ defined as the oxygen uptake that can be sustained for a given period of time. This definition makes sense in sports with constant work requirements, however, for sports with fluctuating intensity this is more complicated. Specifically, successful XC skiing requires a high $\dot{V}O_{2max}$, as well as the ability to reach a high peak oxygen uptake ($\dot{V}O_{2peak}$) and to ski efficiently according to the terrain in the different sub-techniques (Sandbakk and Holmberg, 2017). Furthermore, in XC skiing, even if the mean intensity is aerobic (i.e., 90-95% of $\dot{V}O_{2max}$), relatively substantial anaerobic contributions are shown to support aerobic energy delivery (Losnegard, 2019). There are large variations in the exercise intensity during races according to the change between uphill, flat and downhill terrains. Several studies have shown work rates requiring approximately 110–160% of a skiers ‚$\dot{V}O_{2max}$ on relatively short uphill segments during competitions (Gløersen et al., 2018b; Karlsson et al., 2018; Losnegard, 2019), thereby combining nearly maximum aerobic energy delivery with significant amounts of anaerobic metabolic support. While such repeated bursts of high uphill work rates cause the substantial accumulation of fatigue, the strategy is possible due to the natural recovery allowed during subsequent downhill where external power requirements are nearly zero while flat segments also have smaller power requirements than uphills (Losnegard, 2019; Noordhof et al., 2021). Since XC skiers generate particularly high work rates in uphill terrain (Sandbakk et al., 2012a; Andersson et al., 2016; Sandbakk and Holmberg, 2017; Haugnes et al., 2019a), and push the metabolic demands considerably above their $\dot{V}O_{2max}$ during short uphill section, XC skiing additionally requires sufficient levels of anaerobic capacity and the ability to recover and reproduce anaerobic power in downhill sections during competitions (Losnegard et al., 2012; Gløersen et al., 2018b; Karlsson et al., 2018; Losnegard, 2019; Gløersen et al., 2020).

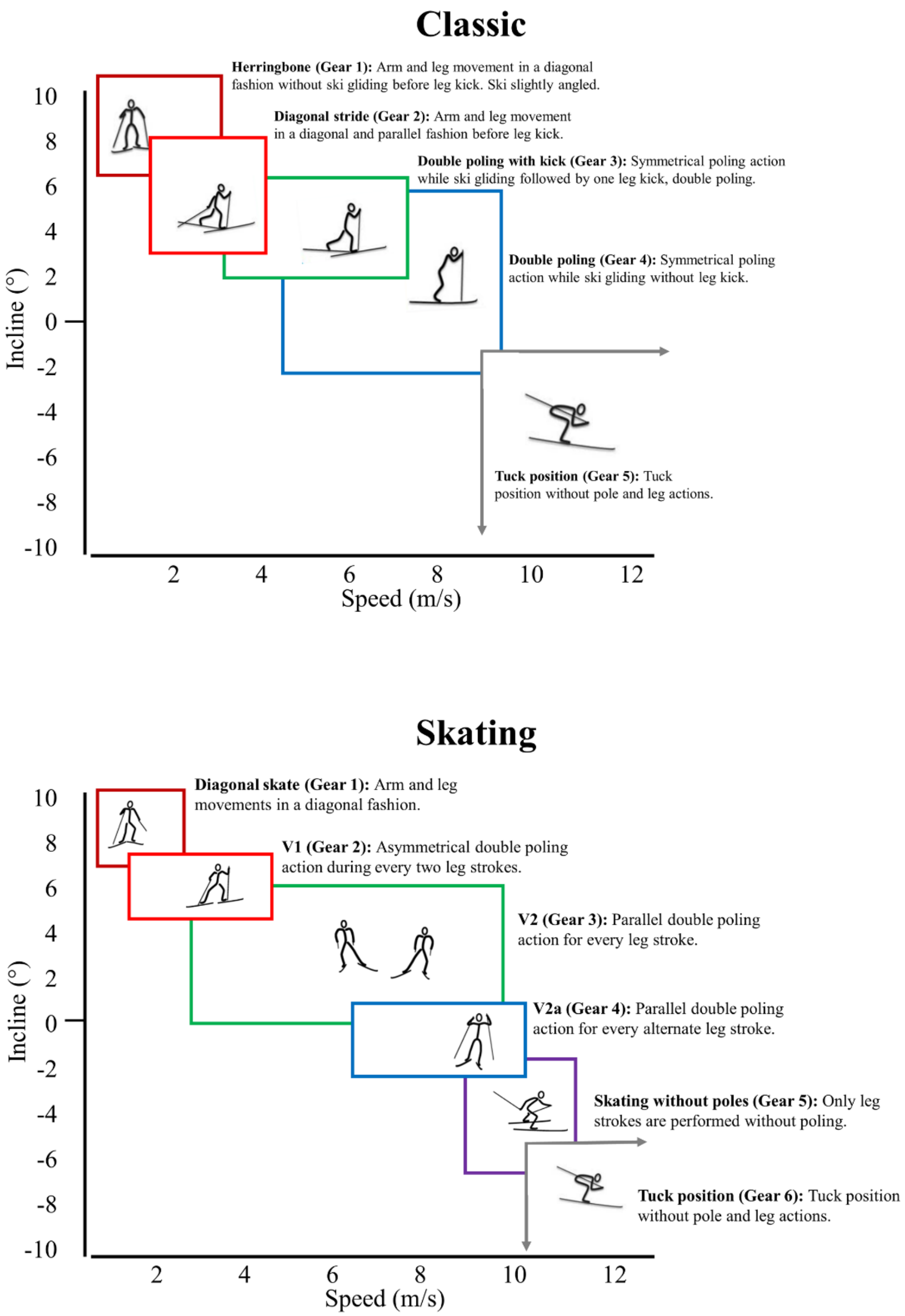


Figure 4 Overview of the sub-techniques in classic and skating, with speed and incline estimates based on previous studies (Stöggl et al., 2014; Marsland et al., 2015; Jang et al., 2018; Stöggl et al., 2018b; Tjønnås et al., 2019). The figure is replicated from (Solli, 2020), printed with permission from the author, and it is a modified version of figure 2 in (Losnegard, 2019).

1.3 Training for XC skiers

The annual training volume of elite XC skiers has been reported to be within the range of 750–950 h (Sandbakk et al., 2011b; Sandbakk and Holmberg, 2014; Sandbakk and Holmberg, 2017) and ~20-30% higher training volume has been reported in elite skiers compared with national-level XC skiers (Sandbakk et al., 2011b; Sandbakk et al., 2016a). Furthermore, the distribution of the training has been found to be approximately 80% at low-intensity (LI), 4% to 5% moderate- and 5% to 8% high-intensity (HI) endurance training, and 10% training strength and speed (Sandbakk and Holmberg, 2017). Here the following definition of the intensity zones have been used: low-intensity training: blood lactate concentration < 2.5 mmol/L, heart rate (HR) < 81% of maximal HR (HR_{max}); moderate-intensity training: blood lactate concentration 2.5–4.0 mmol/L, HR 81–87% HR_{max}; high-intensity training: blood lactate concentration 4.0–10.0 mmol/L, HR > 87% HR_{max}.

Accordingly, even though XC skiing competitions are performed at high-intensity, with high-intensity sessions regarded as a key stimulus in the development of XC skiers, most of the training is performed as long-duration sessions of continues skiing or roller skiing or technical training at low-intensity (Sandbakk and Holmberg, 2017). The reason why so much low-intensity training traditionally has been regarded beneficial for XC skiers is that since the degree of accumulated fatigue from such training is low (Sandbakk and Holmberg, 2017), it allows for a large volume. However, as for high-intensity continuous XC skiing performed in varying terrain, similar sessions during low-intensity also induce significant terrain-dependent fluctuations in power output and HR (Solli et al., 2018; Tjønnås et al., 2019). Accordingly, even if the mean intensity of such sessions is at low-intensity, the intensity during uphills can be much higher, and downhill will be lower (Solli et al., 2018; Haugnes et al., 2019a). As a result of the terrain dependent fluctuations in continuous sessions, the choice of sub-technique, kinematic patterns (Solli et al., 2018), and the loading of arms and legs will be challenged to various degrees depending on the terrain and intensity, and this interval-based physiological and biomechanical stimulus in XC skiing, including the differences between low-intensity and high-intensity skiing, have not been thoroughly explored. The few studies that have been performed to investigate low-intensity versus high-intensity skiing in varying terrain (Solli et al., 2018; Haugnes et al., 2019a) have been performed outdoors on snow, and are limited by a lack of control over external conditions. Also, biomechanical variables, i.e., sub-technique selection, cycle length and cycle rate, have only been studied in classical style (Solli et al., 2018). In addition, since it is difficult to measure physiological responses in the field, only HR that is a proxy for metabolic intensity has been measured. Thus, a comprehensive understanding of the physiological and biomechanical demands of XC skiing under standardized conditions is needed to subsequently be able to measure and correctly interpret low- versus high-intensity responses in the field, especially in the skating style.

1.4 The demands of mass-start competitions

Due to the large variation in XC competition formats (i.e., distance, style, start format), the corresponding race demands, and performance-factors can differ considerably (Sandbakk and Holmberg, 2017). For example, sprint skiers have different physiological characteristics, with higher muscle mass and anaerobic power, than performance-matched distance skiers who are able to produce a higher aerobic power (Losnegard and Hallén, 2014). Accordingly, understanding race-specific demands and associated performance determinants for each competition format is important for optimizing training and race strategies. While individual time-trial competitions in both classic and skating-style are well-described in the literature (Losnegard et al., 2012; Gløersen et al., 2018b; Karlsson et al., 2018; Losnegard, 2019; Gløersen et al., 2020) mass-start competitions, which represent the most common competition format, are virtually unexplored (Losnegard, 2019).

Mass-start competitions in XC skiing were first introduced in the 2002 Olympics (Pellegrini et al., 2018), and, in the most recent Olympics and World Championships, five out of six races for both men and women were performed as head-to-head competitions, in which the winner is the first person to cross the finish line (Pellegrini et al., 2018). In mass-start competitions, all skiers start together, often on narrow tracks with limited possibilities to advance in the field. Accordingly, overtaking in narrow parts of the tracks in the constantly fluctuating terrain requires both tactical and technical flexibility and induces rapid changes in work rate (Pellegrini et al., 2018). Further on, tactical flexibility may also be beneficial for avoiding incidents and disadvantages caused by the accordion effect, which is known to occur in traffic and has been described in road cycling (Trenchard, 2010; Blocken et al., 2018), for example around tight corners or in transition from flat terrain to a steep uphill. Here the athletes in front must reduce speed and thereafter accelerate again, and these fluctuations in speed propagate backwards and typically gradually increase further back in the pack (Trenchard, 2010; Blocken et al., 2018). Although the accordion effect has not been described in XC skiing, the large pack of skiers in mass-start competitions, combined with narrow tracks and fluctuating terrain, likely creates such an effect.

Due to the influence of competitors, individual pacing strategies are more difficult in mass-starts than in individual time-trial competitions even though they are performed on the same racecourses. (Losnegard et al., 2016). In mass-start races in mountain biking (Impellizzeri and Marcora, 2007; Abbiss et al., 2013; Granier et al., 2018) and running (Hettinga et al., 2019), most competitors normally follow the leaders for as long as possible in order to benefit from the drafting effect and thereby improve their chances of winning, as may also be the case in XC skiing. Adopting that strategy will possibly lead to a positive pacing pattern for lower-performing skiers, with a higher relative intensity during the first part of the competition. Such a pacing pattern may be less effective compared to more even pacing strategies shown to be beneficial in individual time trials in XC skiing (Losnegard, 2021). Additionally, XC skiers need to constantly regulate the intensity in relation to the fluctuation terrain. It is well-known that in XC skiing time trials, more than 50% of the total time is spent uphill (Bolger et al., 2015; Losnegard, 2019), and uphill has been found to be the most performance-differentiating terrain (Andersson et al., 2010; Sandbakk et al., 2011a; Bolger et al., 2015; Stöggl et al., 2018a). Although mass-starts are performed in the same tracks as time trials, the distribution of the time according to the terrain types and the pacing pattern has not been explored in scientific literature. Pacing strategy and tactical choices in XC skiing competition are crucial but these choices may consequently influence physiological and biomechanical demands (Abbiss and Laursen, 2008; Pellegrini et al., 2018).

Efficient skiing in constantly changing terrain requires frequent shifts between the different sub-techniques and inherent regulation of cycle length and cycle rate (Pellegrini et al., 2013; Solli et al., 2018). Previous research has shown that faster skiers use more “demanding” sub-techniques (i.e, more G3 versus G2 in skate, and more double poling versus diagonal stride/double poling with a kick in classic) in steeper terrain than slower skiers (Andersson et al., 2010; Marsland et al., 2017). Additionally, while more efficient skiers obtain longer cycle length (Sandbakk et al., 2010; Sandbakk et al., 2012a; Sandbakk et al., 2012b; Sandbakk et al., 2013; Marsland et al., 2017), fast skiing also requires the ability to employ rapid cycles when accelerating at the start, during breakaway attempts and when sprinting at the finish of races (Haugnes et al., 2019b). In this context the understanding of how skiers regulate the power contributions from poles and skis to generate the required propulsion, and how this affects the oxygenation of muscles in arms and legs is unclear, especially in the skating technique. Ultimately mass-starts are commonly decided by a mass sprint or by a sprint between a few remaining contestants, and more seldom by a single skier crossing the finish solo after a breakaway. In all cases, high capacity to produce aerobic and anerobic power, together with high efficiency in the most important sub-techniques, should enable skiers to work at a lower relative intensity to follow the pace, and thereby reduce the accumulation of fatigue before entering the final sprint. The extent to which physiological and biomechanical variables determine the overall performance or different components of mass-starts, particularly the sprint ability following variable intensity XC skiing, is unknown and may be valuable information to further optimize training and competition strategies. In view of this background, more research is needed to increase knowledge related to mass-start demands and performance.

1.5 Micro-pacing strategy in XC skiing

In all endurance sports it is important to optimize the 'pacing'-strategy, i.e., to distribute the energetic resources from start to finish as effectively as possible (Abbiss and Laursen, 2008). As earlier indicated, this is particularly difficult in XC skiing, since efficient distribution of energetic resources in the varying terrain requires a continuous decision-making process based on anticipation of effort, information about the course profile and snow conditions, as well as perception of the current physiological and psychological state.

Overall, XC skiers employ a variable pacing pattern with higher metabolic rates and power production during uphill than flat and downhill terrain (Gløersen et al., 2018b; Karlsson et al., 2018). To further improve performance, refining XC skiers micro-pacing strategy, by adjustments of speed and/or transitions between sub-techniques within or between terrain sections, can be beneficial. A recent study investigated micro-pacing strategies during a classical sprint time trial and revealed that the instant speed during the acceleration phase over hilltops was significantly correlated to the time spent in the subsequent downhill section (Ihalainen et al., 2020). Furthermore, the study indicated that performance in downhill terrain influenced the overall performance, which is especially relevant when the margins between skiers are small (Ihalainen et al., 2020). Therefore, it was hypothesized that increasing speed over specific hilltops to save time in the subsequent downhill without reducing speed in other parts of the track could improve XC skiing performance.

However, for this to be useful, the coaches and XC skiers must know where on the specific racecourse this technique will be beneficial, i.e., specifically on which downhill sections seconds can be saved. XC skiers often perform training sessions on the specific racecourses prior to competitions to optimize technical and tactical solutions. Still, the pacing strategies developed in such sessions are typically based on the experiences of the athletes and coaches, and not on evidence or objective data. In this context, objective feedback based on sensor data would be valuable for helping athletes and coaches to optimize micro-pacing strategies and thereby improve performance in the upcoming competition (Seeberg et al., 2017; Gløersen et al., 2018b; Tjønnås et al., 2019). It may also be useful to combine the sensor data with video observations that have been shown to be efficient for improving individual feedback when coaching large groups (Sollie et al., 2021).

1.6 Sensor-based measurement techniques in outdoor XC skiing

Over the last years, data from different wearable sensors have been used to assess performance, physiological responses, and kinematic patterns in outdoor XC skiing. In 2021, a consensuses agreement with recommendations concerning how to conduct research on XC skiing were given by a group of highly cited XC skiing researchers (Pellegrini et al., 2021). Here, guidelines for the major biomechanical and physiological methodologies were given. A brief overview of the sensor-based measurement techniques for outdoor XC skiing is given below. With carefully designed protocols, and the different sensor data synchronized to a common timeline it is possible to explore physiological responses, movement technique as a function of the terrain and external condition to get an integrative understanding of XC skiing (Seeberg et al., 2017; Tjønnås et al., 2019). Altogether, the combined use of various wearable sensors with adapted signal processing and smart classification and detection models will offer new and important insights into the interrelated physiological and biomechanical demands of XC skiing.

1.6.1 Speed, location and altitude

Global Navigation Satellite Systems (GNSS) sensors are commonly used to measure outdoor speed, altitude, and position in varying terrains. However, their accuracy may not be sufficient for short distances, such as when measuring the maximal speed or glide of skis (Gløersen et al., 2018a). In such instances, different photocells are typically used. Several studies have used sports watches with integrated 1 Hz GNSS devices (Seeberg et al., 2017; Solli et al., 2018; Haugnes et al., 2019a; Tjønnås et al., 2019; Stöggl et al., 2020). Although these GNSS sensors lack the precision to measure instantaneous speed changes, they provide sufficient accuracy for measuring mean distance and speed over relatively long segments (Gløersen et al., 2018a). GNSS sensors with a higher resolution of 10 Hz exist and have been utilized in multiple studies. Their accuracy is more suited for measuring instantaneous speed changes, but they are more costly than the 1 Hz GNSS sports watches. Furthermore, differential GNSS have been used to track the path of individual skiers (Karlsson et al., 2018; Gløersen and Gilgien, 2021). These devices can also map the trajectory of the track and overlay other GNSS traces onto this trajectory, enhancing the accuracy of the elevation and positioning according to the track (Gløersen et al., 2018b; Gløersen et al., 2020; Solli et al., 2020b). Nevertheless, these devices are pricey and the process of measuring the trajectory is time-consuming. Finally, it has been found that the accuracy of all GNSS devices varies with speed, demonstrating lower accuracy at slower speeds.

1.6.2 Physiological measures

Portable sensors for measuring oxygen uptake ($\dot{V}O_2$) have been used in a limited number of studies investigating XC skiing (Doyon et al., 2001; Welde et al., 2003; Larsson and Henriksson-Larsén, 2005). However, these sensors are expensive and especially during cold conditions $\dot{V}O_2$ systems may not be accurate. A recent study found that during indoor cycling the accuracy of a portable $\dot{V}O_2$ sensor was acceptable at 15^{o}C, but that the device was not valid during 0^{o}C or -15^{o}C either at submaximal intensity or at maximal-intensity (Docter, 2022). In addition, a lot of samples were lost due to obstruction of the sampling line (icing). The same accuracy and problems may be expected for other portable $\dot{V}O_2$ sensors in the cold due to the nature of the measurement. Accordingly, it is necessary that the system utilized to determine respiratory parameters must have been validated for the prevailing conditions (i.e., temperature, humidity, altitude, etc.) and tolerate exposure to rain, snow, wind and altitude before use (Pellegrini et al., 2021). Furthermore, since it is not possible to measure $\dot{V}O_2$ validly during outdoor XC skiing competitions, simulated competitions indoors could provide useful knowledge of the integrative physiological and biomechanical demands of competitive XC skiing.

Consequently, in XC skiing, as in other endurance sports, HR measured by electrodes placed at the chest is the most common surrogate for physiological load outdoors in the field (Solli et al., 2018; Haugnes et al., 2019a). HR measured by photoplethysmography sensors (often placed on the bottom side of a sports watch on the wrist) have a low robustness towards movements (Prieto-Avalos et al., 2022), but may provide a valuable tool for measuring resting HR and heart rate variability (HRV) that can be used to assess recovery since the sports watches are truly unobtrusive and comfortable to wear.

HR electrode-belts are commonly used during daily training by both athletes and recreational skiers and provide a common tool for steering the intensity. However, interpretation of the individuals HR requires knowing his/ her maximal HR that must be measured with appropriate methods (Pellegrini et al., 2021). In addition, the instantaneous HR has a high-frequency variability, i.e., HRV, that is regulated by the autonomic nervous system and its sympathetic and parasympathetic branches, and therefore needs to be averaged over some heart beats to give a representative value. Also, since HR are known to drift over time, especially during high-intensity, and have an asymmetrical response to increase/decrease of workload (Whipp et al., 1982), the further complexity of the fluctuating intensity of XC skiing complicates the interpretation of the load/relative intensity according to the varying terrain. To summarize, since HR only is used as a proxy for metabolic intensity and $\dot{V}O_2$ during interval-based and fluctuating intensity (Boulay et al., 1997; Bot and Hollander, 2000; Tucker et al., 2006; Staunton et al., 2022a), more knowledge is needed from indoor studies with gold reference $\dot{V}O_2$-sensor and varying course profiles on how to interpret HR-values during outdoor XC skiing in varying terrain.

Tissue-muscle oxygenation (the percentage of oxygenated hemoglobin) as measured and estimated with near-infrared measurement sensors (NIRS) has been shown to reflect oxygen uptake more accurately and respond faster to changing exercise intensity when compared to HR (Born et al., 2017), and has been proposed to be used to monitor individualized intensity zones during training and competition, also in XC skiing. However, since the various XC skiing techniques generally involve the whole body, muscle-specific intensity may differ from systemic central intensity and fatigue mechanism. In this context NIRS measurements may provide detailed knowledge when comparing local metabolic demand and intensity between different muscle groups. To date, NIRS measurements has only been used in a few XC skiing studies (Im et al., 2001; Sandbakk et al., 2015a; Stöggl and Born, 2021) and more research is needed to assess whether NIRS measurements has the robustness, accuracy and signal-to-noise ratio to validity estimate muscle oxygenation and to give valuable input and increase knowledge of the contribution of various upper body, lower body, and trunk muscles as a function of sub-technique, terrain and intensity in XC skiing.

Other potential physiological measures consist of blood lactate concentration, skin temperature and surface electromyography (sEMG). Blood lactate concentration is a valuable measure for intensity below the lactate threshold (Goodwin et al., 2007) and can be measured outdoors by portable devices, however, for XC skiing only point measurements during rest is feasible. Continuous skin temperature can give input to the assessment of cold- or heat stress (Seeberg et al., 2013; Austad et al., 2018) and support interpretation of other measurements, especially when measured at the upper body under clothing when the correlation with core temperature is high (Austad et al., 2018), but have to a low degree been used in XC skiing. sEMG has been used to study muscle-activation and fatigue of specific muscles during for example XC sprint skiing and different sub-techniques in both classical and skate (Zory et al., 2006; Zory et al., 2011; Göpfert et al., 2016). However, sEMG are prone to noise from motion artifacts, especially during dynamic conditions, is expensive and requires a lot of competence and effort to interpret the results.

1.6.3 Movement analysis

Inertial Measurement Units (IMUs), consisting of three-dimensional accelerometers, gyroscopes, and sometimes magnetometers, have demonstrated potential in providing data suitable for measuring movement patterns in outdoor XC skiing. This bypasses the need for resource-intensive methods such as video analysis. However, raw data from IMUs need to be processed through models or algorithms to yield useful information.

A crucial feature of XC skiing lies in its subdivision into different sub-techniques, with all performance-related measures linked to these distinct sub-techniques. As such, the automatic detection of sub-techniques forms the foundation for providing insights into the interaction between performance, physiological parameters, technique, speed, frequency, power, and efficiency across different terrains.

Different approaches for robust sub-technique detection have been addressed in many outdoor XC studies (Marsland et al., 2017; Seeberg et al., 2017; Jang et al., 2018; Marsland et al., 2018; Solli et al., 2018; Takeda et al., 2019; Tjønnås et al., 2019; Trøen et al., 2020), yielding varying results. Data from a single IMU has been used to detect cycles and classify the primary sub-techniques in classical style and the corresponding macro-kinematics (Marsland et al., 2018; Solli et al., 2020a; Solli et al., 2020b). Multiple IMUs have been utilized for more robust cycle detection and a more detailed sub-technique classification in classical style sub-techniques (Rindal et al., 2017; Seeberg et al., 2017; Jang et al., 2018; Solli et al., 2018; Tjønnås et al., 2019). They have also been used to assess micro-kinematics and the timing between different body parts (Seeberg et al., 2017; Tjønnås et al., 2019). Some studies also address detection of sub-techniques by IMUs in skate style (Stöggl et al., 2014; Jang et al., 2018). However, these approaches have only been tested on a limited number of skiers and types of terrain.

In addition, data from differential GNSS placed on the head has been used for automatic sub-technique detection in classical style (Takeda et al., 2019) and the three main sub-techniques in skate (Gløersen and Gilgien, 2021), however these sensors can be cumbersome. In summary, while several studies have been conducted to classify sub-techniques in the classical style, studies and algorithms that detect the skate style were scarce at the time this thesis was initiated.

The choice of sub-technique, kinematic patterns, and the loading of arms and legs will be challenged to various degrees depending on the terrain and intensity. Measurement and evaluation of pole force and the force between the ski boots and skis may help to interpret the kinematic pattern observed. The ground reaction forces associated with XC or roller skiing can be measured directly or estimated in several different ways; with external force platforms, pressure or sensor insoles in the ski-boots or force sensors integrated into the skis, bindings and/or poles. For field-measurements, only portable systems can be used, and currently only insoles with pressure sensor are commercially available. Several outdoor studies have measured the forces exerted through the poles using poles fitted with devices such as force transducers or strain gauges both on roller skis (Millet et al., 1998; Mende et al., 2019; Sunde et al., 2019), and on snow (Stöggl et al., 2008; Mikkola et al., 2013; Andersson et al., 2014a; Wiltmann et al., 2016; Nikkola et al., 2018). Multiple studies have also measured forces exerted through the skis on snow (Stöggl et al., 2008; Andersson et al., 2014a; Göpfert et al., 2016; Wiltmann et al., 2016; Meyer et al., 2022b). Overall, these investigations have found that the best skiers have more powerful, explosive propulsive phases in some of the sub-techniques; i.e., particular in DP, DS and G3 (Holmberg et al., 2005; Lindinger et al., 2009a; Stöggl and Holmberg, 2011; Mikkola et al., 2013; Andersson et al., 2014b), and that they have more symmetrical distribution of propulsive actions between the upper and lower body (Sandbakk et al., 2013), as well as between the so called “strong and weak sides” in the skating sub-techniques (Stöggl and Holmberg, 2015). Still, the understanding of how skiers regulate the power contributions from poles and skis to generate the required propulsion in the different sub-techniques in the changing terrain, and how this affects the oxygenation of muscles in arms and legs is unclear, especially in the skating technique.

2 Purpose of the thesis

Against this background, the primary objective of this thesis was to investigate physiological responses and movement technique and their associations with training intensity and performance in XC skiing using sensor data, with a particular emphasis on mass-start competitions and the skating technique. Inherently, we aimed to utilize sensor-based information to change behavior and thereby improve performance.

Four connected papers were conducted to cover the primary objective of this thesis, including four specific aims. As an initial step, we complemented wearable sensors with standard measurements available in the laboratory under standardized conditions to answer the aims of Paper 1 and Paper 2. Here we used accurate reference sensors and methodology aiming to build competence on how to interpret data from sensors employed outdoors in the upcoming studies. Thereafter, two outdoor studies were performed, one study during an official mass-start competition (Paper 3) and one intervention study with two simulated time trials (Paper 4). The outline of the thesis including the interrelations between the four papers are illustrated in **Figure 1**, while the specific aim and the approach of each paper are given below.

Paper I – **Aim:** To investigate the physiological and biomechanical responses to low-intensity (LI) and high-intensity (HI) roller ski skating on varying terrain and compare these responses between training intensities.

> **Approach:** This was achieved by conducting an indoor study at low- and high-intensity on a treadmill under controlled conditions, using both gold standard reference sensors (motion cameras, respiratory measurements, muscle oxygenation) and wearable sensors (HR, IMUs, poles with force measurements). The protocol consisted of two 21-min bouts (7 × 3-min laps) at low- and high-intensity with the same set inclines and intensity-dependent speeds (LI/HI: distance: 5.8/7.5 km, average speed: 16.7/21.3 km/h).

Paper II – **Aim:** To investigate physiological and biomechanical determinants of sprint ability in a simulated mass-start setting following variable intensity exercise when roller ski skating.

> **Approach:** This was achieved by investigating physiological and biomechanical determinants of a simulated mass-start competition in roller ski skating on a treadmill using both gold standard reference sensors (motion cameras, respiratory measurements, muscle oxygenation) and wearable sensors (HR, IMUs, poles with force measurements). The protocol consisted of an initial 21-min bout with a varying track profile, designed as a competition track with preset inclines and speeds, directly followed by an all-out sprint with gradually increased speed to rank

their performance. The initial part was projected to simulate the “stay-in-the-group” condition during a mass-start, while the all-out-sprint was designed to assess the residual physiological capacities required to perform well during the final part of a mass-start race.

Paper III – **Aim:** To investigate speed profiles, pacing strategies, group dynamics and their performance-determining impact in an XC skiing mass-start competition.

Approach: This was achieved by measuring and exploring continuous speed, pacing and race-dynamics in relation to the varying terrain in a FIS regulated XC skiing mass-start competition on snow. The mass-start was performed in skate, was part of the 2022 Norwegian senior cup and broadcasted on national tv. Speed and position were measured by attaching GNSS-sensors to the upper back of the skiers and subjective data was captured by an online questionnaire after the race.

Paper IV – **Aim:** To investigate the performance effects of video- and sensor-based feedback for implementing a terrain-specific micro-pacing strategy in XC skiing.

Approach: This was achieved by conducting an intervention study on national-level male XC skiers equipped with GNSS, IMU and HR sensors. Following a simulated 10-km skating time-trial on snow the skiers were randomly allocated into an intervention (INT) or control group (CON), before repeating the race two days later. Between races, the intervention group received video- and sensor-based feedback through a theoretical lecture and a practical training session aiming to implement a terrain-specific micro-pacing strategy focusing on active power production over designated hilltops to save time in the subsequent downhill.

3 Methods

The methods presented here provide a summary of the methods used in the original papers, where the specific details are thoroughly described.

3.1 Ethics declaration

The Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for such studies. Therefore, the studies were done in accordance with the institutional requirements from NTNU and in line with the Helsinki declaration. All skiers provided written informed consent to voluntarily take part in the studies and were informed that they could withdraw from the study at any point in time without providing a reason. Approval for data security and handling was obtained from the Norwegian Center for Research Data (700549) in advance of the study.

3.2 Participants

An overview of all included skiers in the different studies, along with their characteristics (mean value ± standard deviation (SD)), is given in **Table 1**. All participants in this thesis were males, ranging from national- to world-class skiers (McKay et al., 2022). In total, 98 athletes were recruited, with 84 of those included in one or two studies.

The initial data collection (for Paper 1 and Paper 2) was conducted indoors on a treadmill. Thirteen senior national-level athletes, consisting of eight XC skiers and five biathletes, were recruited. All 13 athletes were included in the simulated mass-start competition (Paper 2), while only the nine athletes that were able to complete the protocol without breaks were included in the training-intensity study (Paper 1).

Data for the real mass-start competition on snow (Paper 3) were gathered during the FIS regulated senior skate competition in Norwegian Cup in Gjøvik in January 2022. Here, the 57 top-ranked skiers were recruited and equipped with 10 Hz GNSS sensors, and later followed up with an online questionnaire. Ultimately, 45 skiers were included in this study.

Data collection for Paper 4 was conducted on snow in Meråker, during April 2021. Twenty-seven junior and senior male skiers volunteered to participate in the study, with 26 completing the full protocol and thus included. Additionally, two females completed the protocol for Paper 4, but were not officially included in the study due to a too small cohort.

Table 1 Anthropometric and physiological characteristics (mean value ± standard deviation (SD)) for the included skiers of the different studies. In Paper 4 data is given with respect to the intervention group (INT) and the control group (CON).

	Paper 1 **Indoor** **LI vs HI**	**Paper 2** **Indoor** **Simulated mass-start**	**Paper 3** **On snow** **mass-start race**	**Paper 4** **On snow** **Simulated time trials**
Included (recruited)	9 (13)	13 (13)	45 (57)	26 (28) INT: 14 CON: 12
Age [years]	26 ± 2	25 ± 3	All: 24 ± 3 R1-10: 26 ± 3 R11-20: 23 ± 2 R21-30: 24 ± 2 R31-40: 22 ± 2	INT: 20 ± 1 CON: 19 ± 1
$\dot{V}O_{2max}$ [mL/(min·kg)]	70.6 ± 3.3	69.5 ± 3.6		INT: 71.5 ± 4.5 CON: 72.4 ± 3.5
BMI [kg/m^2]	23 ± 1	23 ± 1	All: 23 ± 1 R1-10: 23 ± 1 R11-20: 23 ± 1 R21-30: 23 ± 1 R31-40: 23 ± 1	INT: 24 ± 1 CON: 23 ± 1
Distance FIS points	36 ± 16* (n=6)	47 ± 21* (n=9)	All: 48 ± 18 R1-10: 26 ± 7 R11-20: 42 ± 11 R21-30: 56 ± 13 R31-40: 61 ± 15	**

INT = intervention groups, CON = control group. $\dot{V}O_{2max}$= maximal oxygen uptake
R1–10 denotes ranks 1 to 10, R11–20 ranks 11 to 20, R21–30 ranks 21 to 30, and R31–40 ranks 31 to 40. *Without the 3 (Paper 1) / 4 (Paper 2) biathlons that do not have FIS points.
** Covid19 season (2020) with few competitions and a mix of junior and senior skiers with a different FIS system so not relevant

In addition to the participants described above, 37 datasets from skiers ranging from recreational- to national-level skiers were recruited to the data collections that were used to develop the model for cycle detection and sub-technique classification.

3.3 Study designs

The aims of this thesis were accomplished in four studies based on data from three different data collections; the connection between the different studies is shown in **Figure 1**.

3.3.1 Low- vs. High-Intensity (Paper 1) and Simulated mass-start race (Paper 2)

Paper 1 and Paper 2 were performed indoors during controlled conditions, where the skiers and biathletes performed a protocol while roller ski skating on a treadmill. Physiological responses and biomechanical variables of the skiers/biathletes were measured using both wearable sensors and laboratory specific sensors. The protocol consisted of three consecutive parts performed on the same day, each with the same preset load for all skiers: a) a 21-min low-intensity bout to simulate a low-intensity training (Paper 1) or familiarization of the racecourse (Paper 2), b) a 21-min high-intensity bout to simulate a mass-start (Paper 2) or a high-intensity training session (Paper 1), and c) an all-out sprint (AOS) immediately following the 21-min high-intensity with gradually increasing speed until exhaustion to assess the residual physiological capacities required to perform well during the final part of a mass-start race (Paper 2). Based on pilot testing and the performance level of the participants, speeds were chosen so that some skiers (the less good ones) would likely not manage to complete the whole high-intensity session/simulated mass-start (simulating that the skiers were not able to " stay-in-the-group"), while the best skiers would be well able to complete it. Accordingly, at any time, skiers could take an unlimited number of 30 s breaks (by grabbing the rope at the front of the treadmill, simulating tuck).

The track was organized as seven identical 3 min laps consisting of four different segments simulating a moderate uphill (S1), a flat segment (S2), a steep uphill (S3) and a simulated downhill (S4) (**Figure 5**). The profile of the track was designed according to international competition rules (International Ski and Snowboard Federation (FIS), 2022), where the main skate sub-techniques (G2, G3, G4, G7 (tuck)) could naturally be utilized, however the skiers could freely select sub-techniques themselves, see **Figure 5**.

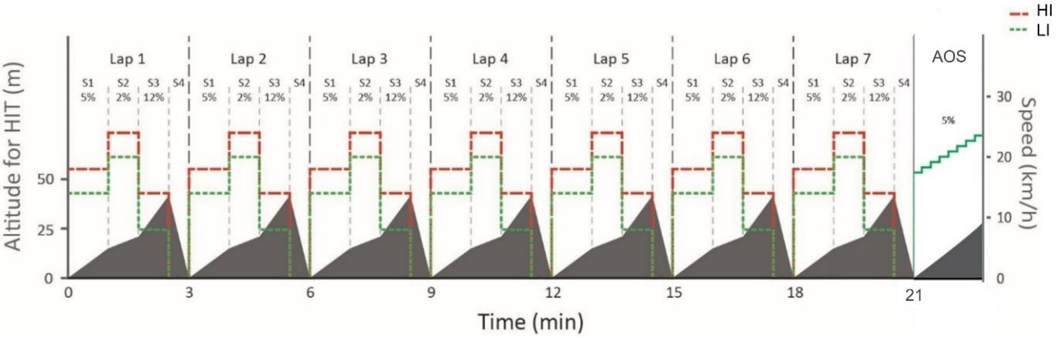


Figure 5 Protocol showing the speed of the treadmill for both the 21 min low-intensity (LI) and high-intensity (HI) bouts / simulated mass-start competition and changes in simulated altitude for the high-intensity session. The high-intensity bout was directly followed by an all-out incremental sprint (AOS) with gradually increased speed each 15 s until exhaustion. The course was divided into seven 3-min laps, each containing four segments (i.e., S1–S4) with the same inclines but different speeds for low- and high-intensity.

3.3.2 Mass-start competition (Paper 3)

Speed profiles of 57 out of 143 male seniors were measured with high-end GNSS sensors in a 21.8 km (Lap 1-6) national mass-start competition in the skating style. Parts of the starting field is shown in **Figure 6**. Within three weeks after the competition, the skiers completed an online questionnaire gathering self-reported anthropometrical characteristics as well as quantitative and qualitative data concerning planned and actual tactics during the competition, speed profiles, and perceived opportunities and challenges. Skiers ranked from 1 to 40 were split into four performance-groups: R1–10 for ranks 1 to 10, R11–20 for ranks 11 to 20, R21–30 for ranks 21 to 30, and R31–40 for ranks 31 to 40.

Figure 6 Parts of the starting field of the FIS regulated mass-start competition in Paper 3. Photo: NTNU.

To enable lap-to-lap analyses, a lap-segment (length, 3550 m; maximal height difference, 42 m; total climb, 114 m) was defined for Lap 2-6 by excluding the first few meters from the start- and finish-line. This lap was further divided into 14 segments (S1-S14) based on the type of terrain, see **Figure 7** for 2D elevation profile and **Figure 8** for 3D visualization of this lap-segment. The total uphill, flat, and downhill sections constituted 37.2%, 20.4% and 42.4% of the total lap-distance, respectively. In addition, a lap-segment was made for Lap 1 which was shorter than the other laps (length, 3170 m; maximal height difference, 21 m; total climb, 93 m), here the steepest downhill with a sharp curve and the corresponding uphill were removed due to limited snow conditions for the safety of the skiers.

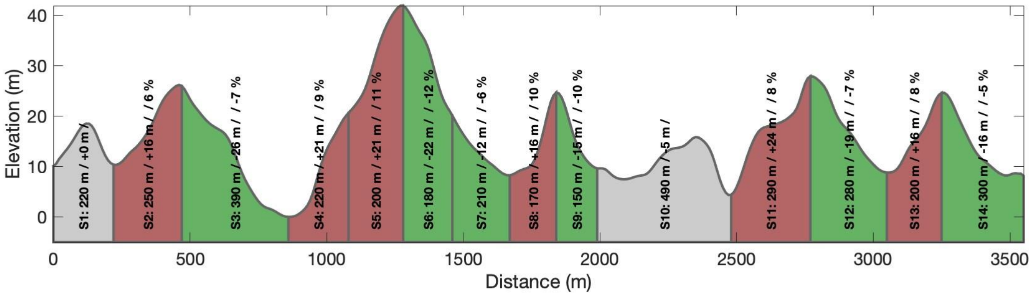


Figure 7 2D profile of the racecourse used in Lap 2 to Lap 6 showing elevation [m] as a function of lap-distance divided into different terrain segments (S1-S14) with segment distance [m], climb [m], and inclination [%] visualized. Lap 1 was shorter than the other laps due to snow conditions and consisted of all segments except S5 and S6. The uphill segments are displayed in red, flat sections in grey, and downhill sections in green. The figure is copied from Paper 3.

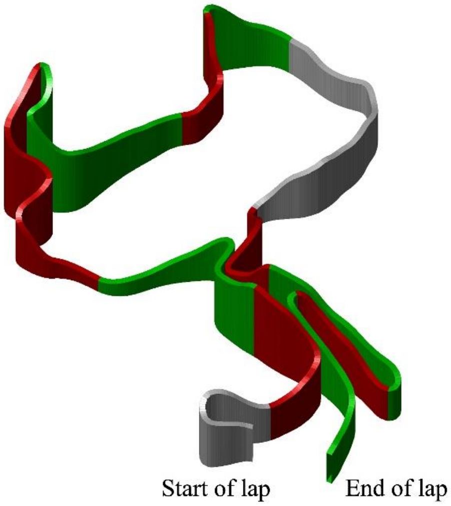


Figure 8 3D visualization of the racecourse used in Lap 2 - Lap 6. The uphill segments are displayed in red, flat sections in grey, and downhill sections in green. The figure is copied from Paper 3.

3.3.3 Improving micro-pacing (Paper 4)

Paper 4 was performed on snow in a 10 km FIS–homologated course. The skiers performed two simulated time-trial races (Race 1 and Race 2) in the skating technique separated by 48 hours. The competition consisted of 3 laps of 3.2 km and was performed with a self-selected lap-to-lap pacing strategy (i.e., macro-pacing). The racecourse exhibited a varied topography based on a course profile divided into uphill (38%), flat (17%), and downhill (45%) segments, with a total climb of 306 m (3 × 102 m) (**Figure 9**). Prior to both races, the skiers performed warm-up procedures consisting of one lap of 3.2 km low-intensity skiing before performing two 20 m maximal speed (V_{max}) tests in flat terrain, followed by two 20 m V_{max} tests in uphill terrain.

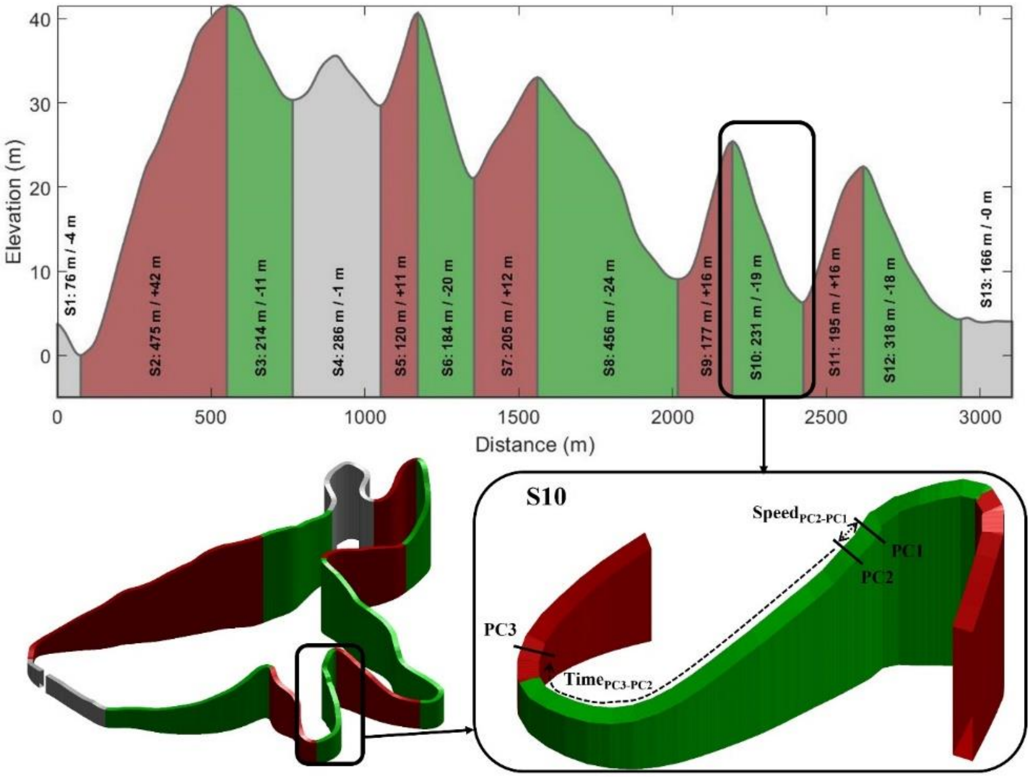


Figure 9 The racecourse (3*3.2km) used in both races in 2D divided in segments (S1-S12), in 3D and downhill S10 with placement of photocells and definition of the two derived measures from photocells; Speed$_{\text{PC2-PC1}}$ and Time$_{\text{PC3-PC2}}$. The figure is taken from Paper 4.

After Race 1, the skiers were randomly allocated into an intervention group (INT) or control group (CON) balanced for starting time, performance in segment 10 (see **Figure 9**) and race-performance. Between races, INT received video- and sensor-based feedback through both a theoretical and a practical training session (a picture from the session shown in **Figure 10**), while CON only received race results and performed a training session with the same duration and intensity, but no feedback on micro-pacing.

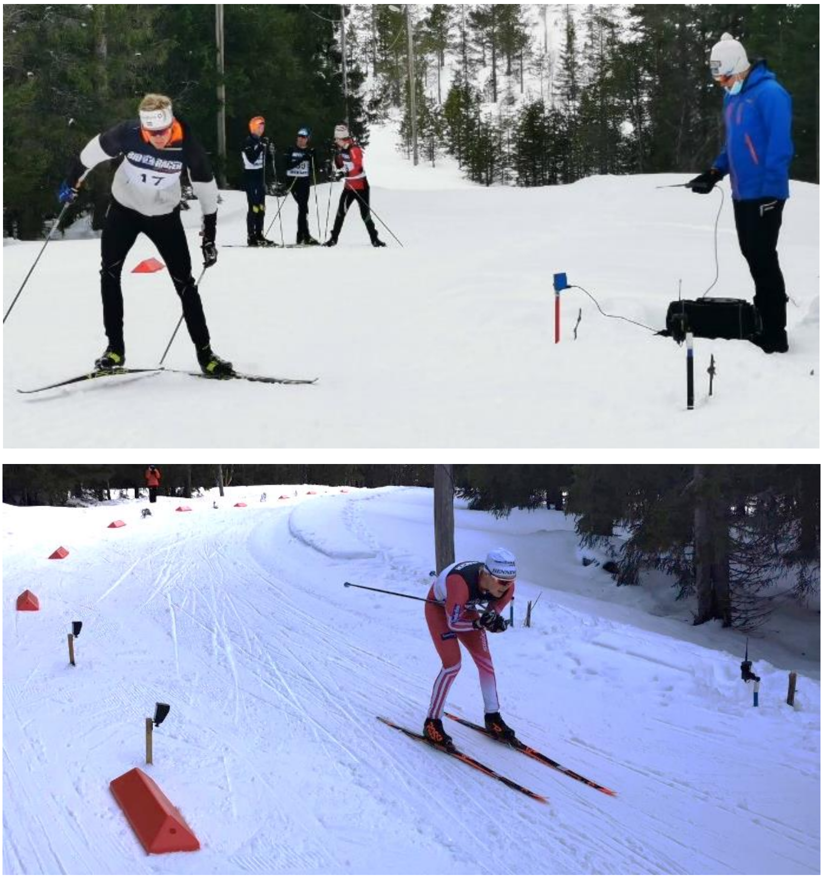


Figure 10 Picture from the practical training session during Paper 4 (top) and a skier passing the "hilltop" during Day 2 (bottom). Photo: NTNU.

In the 45-min theoretical group session, the speed profile (measured by GNSS) in segment 10 of each skier was shown along with the corresponding speed profile of the fastest skier. Subsequently, video footage of the first part of the same segment was shown for each skier, with a brief discussion with the skier on the potential technical and tactical improvements. In the practical training session, the skiers trained in segment 10 and segment 12 (see **Figure 9**) with different technical and tactical strategies, aiming to increase speed in the specific segments but without reducing speed in other parts of the track.

Snow friction was not measured throughout the races, but based on the overall results, there was a lower friction coefficient during Race 2 compared to Race 1 which resulted in significantly higher speeds and better overall performances during Race 2. The conditions also changed within both days, with light snow falling during parts of Race 1 and the sun peeking through the skies during parts of Race 2.

3.4 Overview of sensors

An overview of the specific sensors and the derived features in the different studies are displayed in **Table 2**.

In Paper 1 and Paper 2 both gold standard reference indoor sensors and wearable sensors were used while roller ski skating on a treadmill. $\dot{V}O_2$, HR, NIRS, kinematics and pole forces were monitored continuously (see **Figure 11**), while blood lactate concentration (BLa) and rating of perceived exertion (RPE) were measured directly after each part. In addition, performance-determining variables (gross efficiency (GE) and $\dot{V}O_{2max}$) were measured on a separate day.

Figure 11 Picture from a skier with sensors attached in the indoor data collection for Paper 1 and Paper 2. Photo: NTNU

In Paper 3 only one wearable sensor module (AdMos) was used due to logistic restrictions due to measuring a high number of participants at the same time in a real competition.

In Paper 4, which was performed outdoors on snow, multiple wearable sensors (IMUs, HR electrode-belts, GNSS) in addition to photocells were used, see **Figure 12** for pictures of the wearable sensors. In addition, for Paper 1, 2 and 4 basic physiological and performance variables for the skiers were collected in the laboratory prior to the intervention study.

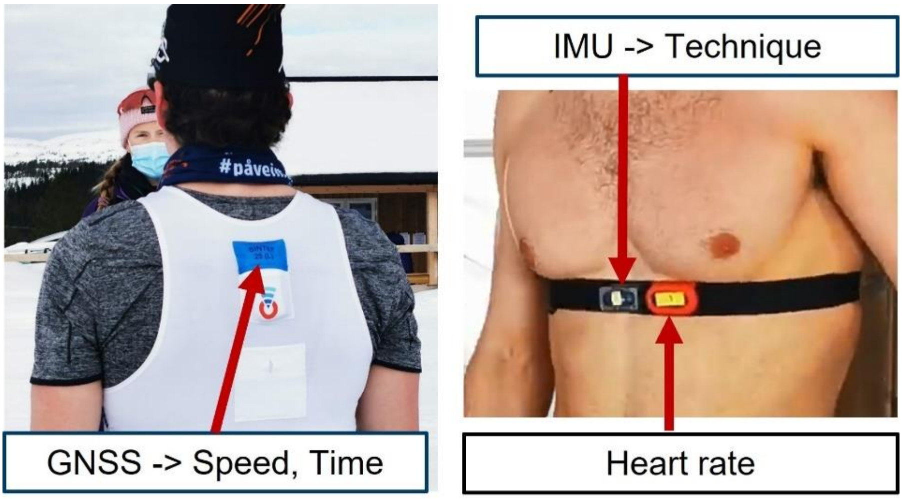


Figure 12 Wearable sensors used in Paper 4. Photo: NTNU.

Table 2 Overview of the used sensors and the derived measures in the different studies.

Sensors	Features	Paper 1 - Indoor Low vs High	Paper 2 - Indoor Simulated Mass-start	Paper 3 - On snow Mass-start Race	Paper 4 - On snow Simulated time trials
Oxygen uptake Treadmill speed, incline	$\dot{V}O_{2max}$ % $\dot{V}O_{2max}$ Average GE	X X -	X X X	- - -	X (lab) - -
NIRS on arms/legs	TSI_{arm}/TSI_{leg}	X	X	-	-
Blood lactate	BLa	X	X		X (lab)
Heart rate	HR_{max} %HR	X X	X X	- -	X X
Motion cameras Force poles	$\%P_{ski}/\ \%P_{pole}$	X	X	-	-
IMU on chest	Cycle length Cycle rate Sub-technique *TotAccVar*	X X X -	X X X -	-	(X)* (X)* (X)* X
IMU on skis and arms	Contact time pole Contact time ski	-	X X	-	-
GNSS (10 Hz)	Speed /Position Track definition Terrain segments	- - -	- - -	X X X	X - -
Differential GNSS	Track definition Terrain segments	- -	- -	- -	X X
Photocells	Time/speed Short segments	-	-	-	X

GE = gross efficiency measured for G2 @12%, G3@5%, G4@2% incline, $\dot{V}O_{2max}$ = Maximal oxygen uptake, %$\dot{V}O_{2max}$ = relative oxygen uptake, NIRS = Near infrared spectroscopy, BLa = blood lactate concentration, HR_{max} = maximal HR, $\%HR_{max}$ = relative HR, IMU = Inertial measurement unit, $TSI_{arm/leg}$ = Tissue Saturation Index measured by the sensor placed on long head of the triceps brachii in the right arm /the vastus lateralis in the

right leg, *TotAccVar* = Total variation of chest acceleration on hilltop (i.e., a metric for biomechanical intensity), GNSS = Global Navigation Satellite Systems,
*Derived, but not included in the papers.

3.5 Model for cycle detection and sub-technique classification:

3.5.1 Datasets

As a basis for Paper 1, Paper 2 and Paper 4, a method was developed to automatically detect sub-techniques and associated temporal patterns (e.g., cycle time, cycle length, cycle rate) in skate based on the methodology used in for the same purpose in classic style (Rindal et al., 2017). The input to the model was sensor data from an IMU placed on the chest of the skiers. To train and test the model data 37 skiers were used, while skating indoors on a treadmill or outdoors during various conditions and tracks. The datasets were partly available from other projects, and partly collected for this purpose. To enable generalization, the datasets were from skiers with varying skills level ranging from recreational-to national level skiers, and the data were collected both indoors on a treadmill and outdoors during various snow conditions, temperature, and tracks.

Combined, all data resulted in a total dataset consisting of 28461 cycles that were manually labeled according to six different classes: Class 1 = Other, Class 2 = G2 left, Class 3 = G2 right, Class 4 = G3, Class 5 = G4 and Class 6 = G5. Here “Other” consisted of G7 (tuck position), different turn techniques, transitions, not skiing etc. Before labeling, the accelerometer data was downsampled to 20 Hz and synchronized in time with video of the skier. The 37 datasets from different skiers were further separated into the categories training-/validation- or test-data. Datasets from 29 of the 37 skiers, 21 collected indoors (level of skiers: 13 national/8 recreational) and 8 collected outdoors (level of skiers: 6 national/2 recreational), were used to train (19910 cycles) and validate (2212 cycles) the machine learning model. The distribution of the 22 122 cycles in the different sub-techniques is shown in **Table 3**. The remaining 8 datasets, consisting in a total of 6339 cycles (5 outdoor on national/junior skiers, 3 indoor om national level skiers) were used to test the model (**Table 3**).

Table 3 Distribution of sub-techniques in the dataset used for training and validation.

Total	**Other**	**G2 left**	**G2 right**	**G3**	**G4**	**G5**
22122	2174	3777	3428	5125	5574	2044

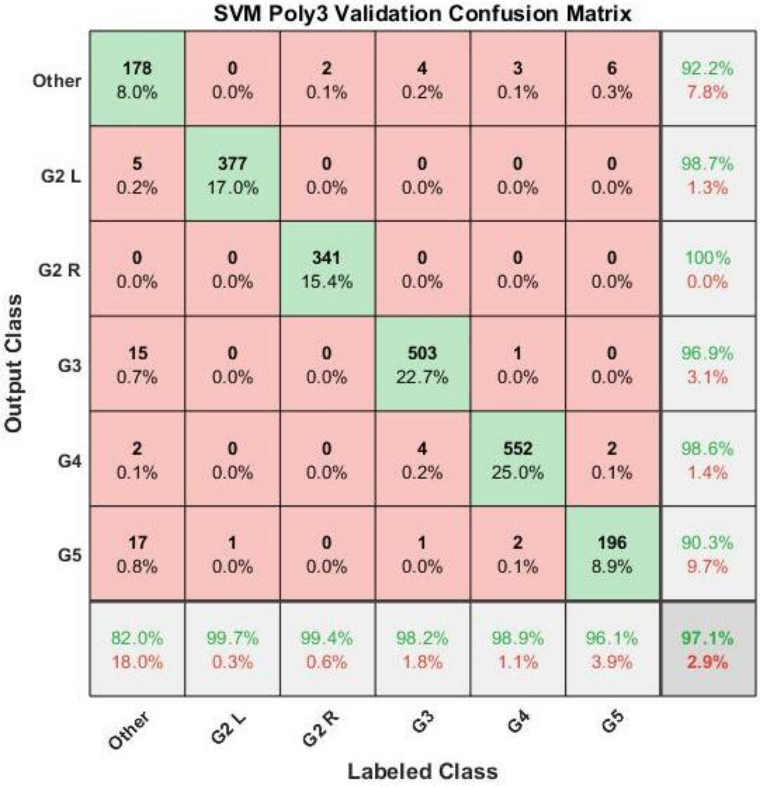
3.5.2 Description of methodology

Only the accelerometer data from the IMU was used for cycle detection and sub-technique classification. Originally, the collected 3D accelerometer data had a resolution ranging from 128-512 Hz, but before further processing the data in each axis were downsampled to 20 Hz. The data were manually labeled using synchronized video and sensor data.

First a method for cycle detection was developed. Several configurations were explored, and the sidewise movement of the upper body, represented by a heavily filtered accelerometer-signal in the corresponding direction (Gaussian low-pass filter with 0.25 s standard deviation in the time domain), was found to be an adequate predictor for correct cycle detection across the sub-techniques. The start of the cycle was defined as the point when the upper body was in a left position with the lowest acceleration.

The sub-technique classification algorithm was based on using the accelerometer data as input to a machine learning model. Here, all three axis of the accelerometer data was used. The data was filtered with Gaussian low-pass filter with 0.0875 s standard deviation in the time domain to remove high frequency noise and movements not contributing to the separation of sub-techniques. A feature vector describing each cycle was made consisting of a total of 94 features. For each axis 30 features (a total of 90 features) was created by interpolating or decimating hthe samples using the same methods as in the classical style model (Rindal et al., 2017). In addition, 4 more features were added, i.e., the original length of the cycle given in samples (1 feature) and the normalized sum of the samples from each axis (3 features). Several different machine learning models and settings were explored, and a support vector machine (SVM) model (with polynomial order 3) was chosen. The SVM model was implemented using the Machine Learning Toolbox in MATLAB 2018b (MathWorks, Natick, MA, USA) and trained on 90% of the data designed for training/validation. The validation data set (10%) was used to select and tune the model using an iterative methodology.

The trained SVM model resulted in an overall accuracy of 97.1% on the validation set, and 99.2% on the combined validation/training set. A confusion matrix for the validation data is presented in **Figure 13**.



SVM Poly3 Validation Confusion Matrix

Output Class

	Other	G2 L	G2 R	G3	G4	G5	
Other	178 8.0%	0 0.0%	2 0.1%	4 0.2%	3 0.1%	6 0.3%	92.2% 7.8%
G2 L	5 0.2%	377 17.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	98.7% 1.3%
G2 R	0 0.0%	0 0.0%	341 15.4%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
G3	15 0.7%	0 0.0%	0 0.0%	503 22.7%	1 0.0%	0 0.0%	96.9% 3.1%
G4	2 0.1%	0 0.0%	0 0.0%	4 0.2%	552 25.0%	2 0.1%	98.6% 1.4%
G5	17 0.8%	1 0.0%	0 0.0%	1 0.0%	2 0.1%	196 8.9%	90.3% 9.7%
	82.0% 18.0%	99.7% 0.3%	99.4% 0.6%	98.2% 1.8%	98.9% 1.1%	96.1% 3.9%	97.1% 2.9%

Labeled Class

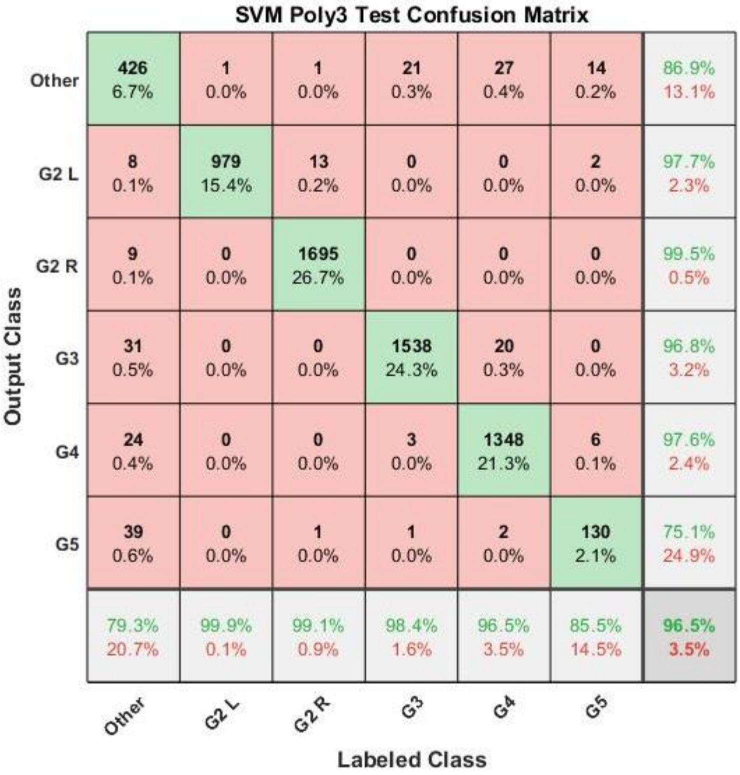
Figure 13 Confusion matrix for the cycles in the validation data. The overall accuracy of the validation dataset was 97.1%.

3.5.3 General test of model

SVM model achieved a total classification accuracy of 96.5% on the test-data, the specific accuracy of each dataset is given in **Table 4**. The indoor datasets had overall accuracy above 97% while the outdoor datasets had lower overall accuracy (91-95%). The confusion matrix of the cycles of the test data set is given in **Figure 14**. Here the category "Other" and G5 had the lowest sensitivity (79% and 86%) (lower row) while the most common sub-techniques (G2 left and right, G3 and G4) had the highest precision with 96-99% (rightmost column).

Table 4 Number of cycles in each class and accuracy of trained machine learning model on the 8 skiers in the test dataset. Here each row represents one dataset and each column one class.

Dataset [D#-Site]	**Other**	**G2 left**	**G2 right**	**G3**	**G4**	**G5**	**Accuracy**
D1-Treadmill	0	0	654	401	494	0	99.7%
D2-Treadmill	0	0	424	242	330	0	99.9%
D3-Treadmill	0	652	0	521	594	0	97.7%
D4-Natrudstilen	77	40	0	62	2	35	95.8%
D5-Holmenkollen	77	170	0	42	212	6	91.8%
D6-Holmenkollen	71	0	201	49	3	22	91.9%
D7-Meråker	146	98	209	115	27	63	92.4%
D8-Meråker	166	20	222	131	26	26	92.6%
Total	**537**	**980**	**1710**	**1563**	**1397**	**152**	**96.5%**



SVM Poly3 Test Confusion Matrix

	Other	G2 L	G2 R	G3	G4	G5	
Other	426 6.7%	1 0.0%	1 0.0%	21 0.3%	27 0.4%	14 0.2%	86.9% 13.1%
G2 L	8 0.1%	979 15.4%	13 0.2%	0 0.0%	0 0.0%	2 0.0%	97.7% 2.3%
G2 R	9 0.1%	0 0.0%	1695 26.7%	0 0.0%	0 0.0%	0 0.0%	99.5% 0.5%
G3	31 0.5%	0 0.0%	0 0.0%	1538 24.3%	20 0.3%	0 0.0%	96.8% 3.2%
G4	24 0.4%	0 0.0%	0 0.0%	3 0.0%	1348 21.3%	6 0.1%	97.6% 2.4%
G5	39 0.6%	0 0.0%	1 0.0%	1 0.0%	2 0.0%	130 2.1%	75.1% 24.9%
	79.3% 20.7%	99.9% 0.1%	99.1% 0.9%	98.4% 1.6%	96.5% 3.5%	85.5% 14.5%	**96.5%** **3.5%**

Figure 14 A combined confusion matrix for all the cycles in the test datasets. The overall accuracy was 96.5%.

3.6 Methodology for extraction of sensor-based features

3.6.1 Oxygen uptake

Respiratory variables were measured continuously using open-circuit indirect calorimetry (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany). Expired gas was passed through a mixing chamber and analyzed continuously. The instruments were calibrated against ambient air and a commercial gas with known concentrations of O_2 (15%) and CO_2 (5.85%) before the start of each test. The flow transducer (TripleV, Erich Jaeger GmbH, Hoechberg, Germany) was calibrated using a 3L high-precision calibration syringe (5530 series, Hans Rudolph Inc., Kansas City, Missouri, USA). The data were collected as 10 second mixing chamber values and are given as body weight adjusted oxygen uptake ($\dot{V}O_2$) and as percentage of $\dot{V}O_{2max}$ (%$\dot{V}O_{2max}$).

3.6.2 Tissue saturation index in arms and legs (TSI_{arm}/TSI_{leg})

Tissue-muscle oxygenation was assessed using a wireless NIRS system (Portamon, Artinis Medical Systems, the Netherlands) consisting of two optodes, each with three transmitters and one receiver. All transmitters emitted light at wavelengths of 760 and 850 nm and used a sample rate of 10 Hz. The optode sites were shaved before placement. The two optodes were placed on the vastus lateralis of the right leg and the long head of the triceps brachii on the right arm and secured with tape and elastic bandages before they were covered with a black cloth to prevent the interference of ambient light. At the end of the test, skinfold thickness was measured (three times) at the sites of optode placement using a skinfold caliper (Holtain skinfold caliper, Holtain Ltd, Crymych, Walesltain). The data from the different NIRS sensors was collected and synchronized in time by the designated software and the tissue saturation index (TSI) with a Fit factor higher than 99.8% was used in the study. To remove the resulting one second gaps in the NIRS-data from the filtering, it was chosen to interpolate with the average value of the two neighbor points to avoid gap in the data. TSI_{leg} is TSI from the sensor placed on vastus lateralis of the right leg, and TSI_{arm} is TSI from the sensor placed on the long head of the triceps brachii on the right arm.

3.6.3 Blood lactate concentration

In Paper 1 and Paper 2, blood lactate concentration was measured directly after each bout using Biosen C-line Sport lactate measurement system (EKF Industrial Electronics, Magdeburg, Germany) collecting 20 µL blood form the fingertip. The device was calibrated every 60 min with a 12-mmol µL standard concentration.

3.6.4 Heart rate

In Paper 1, Paper 2 and Paper 4, Garmin Forerunner 920XT/935 with HR belt (HRM Run or Pro) (Garmin Ltd., Olathe, USA) was used to continuously measure HR at a sampling frequency of 1 Hz, see **Figure 12**. Relative HR (%HR_{max}) was calculated as % of maximal HR (HR_{max}) for each skier, and HR_{max} was defined as the highest measured value for each person measured at any time during the tests (during the maximal incremental test or in any of the other tests).

3.6.5 Sub-technique detection and cycle length/rate

In Paper 1 and Paper 2, the accelerometer data from an IMU (Physiolog 5 from GaitUp SA, Lausanne, Switzerland) placed on the chest (fastened with Velcro to a HR electrode-belt, see **Figure 12**) was used to automatically detect and classify each individual cycle into a sub-technique using the trained support vector machine learning model described in 3.5. The IMU consisted of a 3D-accelerometer and 3D-gyroscope with sampling frequency 256 Hz, in addition to a barometric pressure sensor with sampling frequency 64 Hz. Data was stored locally on the sensor during the test and later downloaded to a computer. The cycles were classified into the sub-techniques G2, G3, G4, G5 or Other, where Other included transitions between sub-techniques, simulated downhill (G7) and non-skiing activities. The accuracy of the classification model on the data in Paper 1 and Paper 2 was above 99 %. Cycle detection together with treadmill speed were used to derive cycle time, cycle length and cycle rate of each cycle.

3.6.6 Detection of pole- and ski contact time

In Paper 2, accelerometer and gyroscope data from the left and right wrists were used to calculate the contact time for poles (CT_{pole}) by determining the time between initial and terminal pole contact with the ground. On these data, the overall precision for CT_{pole} was 18 ± 21 ms (6.5% ± 11.5%) and for CT_{ski} was 7 ± 13 ms (0.7% ± 1.0%). Initial contact was set as the first acceleration peak at the beginning of the vibration phase induced by the pole touching the ground, while terminal contact was obtained as the highest acceleration peak close to the minimum angular speed induced by the change in direction of the motion to bring the poles back once the pole push was finished. Ski contact time (CT_{ski}) was calculated using data from the IMUs mounted on the skis. Initial ski contact was defined as the first peak of the pitch angular velocity before a long phase with low angular velocity due to the skis being on the ground, while the terminal ski contact was set as the last negative vertical acceleration peak after the low angular velocity phase, details for the methods are given in (Meyer et al., 2021).

3.6.7 Total acceleration variation over hilltops

In Paper 4, an accelerometry-derived measure that captures the intensity of both active poling and leg kick, named “total variation of chest acceleration” (*totVarAcc*), was used as an indicator of the skiers biomechanical work-intensity on the hilltops. The measure was based on the dynamic part of the acceleration total power signal from the chest and is given by the following equation:

$$totVarAcc = \sum_{a\epsilon(x,y,z)} \left\{ \frac{1}{N} \sum_{i=1}^{N} movvar(a,\omega)_i \right\}$$

Here, a is the acceleration in the x,y,z-direction, N is the number of accelerometer samples recorded on the hilltops and *movvar* (Matlab-function) is the gliding variance with window size $\omega = 5$ seconds, see appendix for details.

3.6.8 Power-distribution between poling and ski push-offs ($\%P_{ski}$/ $\%P_{pole}$)

In Paper 1 and Paper 2, power-distribution between poling and ski push-offs was derived from kinematics measured with motion camera system and force measurements from instrumented ski pole grips. Eight Oqus 400 infrared cameras of the Qualisys motion capture system 139 (Qualisys AB, Gothenburg, Sweden) captured 3D position of passive reflective markers placed bilaterally on the body, on roller skis and poles with a sampling frequency of 200 Hz. The specific body locations of the reflective markers were on the ski boot at the distal end of the fifth metacarpal, the lateral malleolus (ankle), lateral epicondyle (knee), greater trochanter (hip), lateral end of the acromion process (shoulder), lateral epicondyle of humerus (elbow), and styloid process of ulna (wrist). For the pole power measurements one marker was placed on the lateral side of each pole, 5 cm below the handle, and one marker was placed on the lateral side of the pole tips, for calculation of pole direction and thus direction of pole forces. For ski measurements, one marker was placed 1 cm behind the front wheel, and one marker 1 cm in front of the back wheel of each roller ski.

Instrumented ski pole grips (Proskida, Whitehorse, YT, Canada) were used to measure the axial (resultant) force directed along the poles. The data was streamed to a mobile phone via Bluetooth during the measurements and later downloaded to a computer.

Force and kinematics from the motion capture system were synchronized offline for each recorded lap by detecting the first instance of pole touch down on the treadmill belt. This touchdown was defined as the first instant when the pole force reached 10 N.

The body center of mass (CoM) was calculated based on the position data and body segments mass properties according to de Leva (de Leva, 1996). CoM velocity was obtained by numerical differentiation of position data. Instantaneous pole power (P_{pole}) was calculated from pole force (F_{pole}) and CoM velocity (V_{CoM}): [$P_{pole} = F_{pole\_x} \cdot V_{CoM\_x} + F_{pole\_y} \cdot V_{CoM\_y} + F_{pole\_z} \cdot V_{CoM\_z}$] with x, y and z representing components of F_{Pole} and V_{CoM} in the forward-backward (x), sideways (y) and vertical (z) directions (Donelan et al., 2002). P_{pole} was calculated independently for each pole first, and then summed. The difference between work rate (P_{cycle}) and cycle average P_{pole} was interpreted as average ski power (P_{ski}). Relative P_{pole} (%P_{pole}) and relative P_{ski} (%P_{ski}) were calculated as % of P_{cycle} for each skier, and relative $P_{poleleft}$/$P_{polerigth}$ (%$P_{poleleft}$/%$P_{poleright}$) was calculated as % of P_{pole} for each skier.

3.6.9 Outdoor speed, position and altitude

During both outdoor studies, Paper 3 and Paper 4, each skier was equipped with a sensor module consisting of a 10 Hz GNSS receiver in combination with an IMU (Paper 4 – Optimeye S5, Catapult Sports, Melbourne, Australia, Paper 3 – AdMos, Advanced Sports Instruments, Lausanne, Switzerland). In both studies the sensor was placed on the skiers backs in an upraised position, in Paper 3 attached to the inside of the race bibs in a customized pocket while in Paper 4 in a customized bib worn on the torso.

In Paper 3 a 3D profile of the 21.8 km long racecourse was developed based on the GNSS-data by averaging location- and elevation-data of all skiers on all laps with a resolution of 1 m along the racecourse. In Paper 4 course and elevation profiles were determined with a differential global navigation system (Alpha-G3T, Javad GNSS Inc). Dual-frequency (L1 and L2) GPS and GLONASS signals were logged at 25 Hz, and a short baseline kinematic carrier phase differential GNSS solution was calculated using Justin (Javad GNSS Inc) postprocessing software (Gilgien et al., 2014). Positions were smoothed using the differential GNSS solutions accuracy estimates as weighted into a spline filter. In both studies the individual GNSS-tracks were fitted to the corresponding racecourse.

The accuracy of the Optimeye S5 has previously been assessed in XC skiing (Gløersen et al., 2018a), while the AdMos sensor has only been validated for use in alpine skiing (Jølstad et al., 2022). Therefore, to assess the accuracy of the AdMos GNSS receiver in this setting, the times from the GNSS measurements were compared with the official split times provided by the organizer, giving sufficient accuracy for our purpose with a mean offset of less than 0.01 s with standard deviation 0.30 s over all 17 split times and all included skiers (n = 42).

To be able to explore responses to different types of terrain in Paper 3 and Paper 4, the racecourse was divided into uphill, flat, and downhill terrain segments based on position and altitude data from the racecourse. This was done by defining a segment boundary at every point where there was a change between positive and negative gradient in the course profile. The uphill and downhill sections were characterized by a minimum elevation difference of 10 m within the segment while a flat segment was defined when an ascent or decent were less than 10 m. Furthermore, adjacent flat segments were merged into longer segments that in some cases contained relatively uphill and downhill parts with low ascent or decent. (Sandbakk et al., 2016b).

3.6.10 Time/speed measurements in short segments

For short sections, a higher accuracy than possible to get from the body worn 10 Hz GNSS sensors was needed to measure "instantaneous" speed and time in a short segment. In addition, a requirement was that this should be measured during a simulated time trial race and enable direct feedback during the practical training. Therefore, during Paper 4 we used photocell (PC) measurements obtained from a two-way mesh radio transceiver (HC Timing, wiTiming) with 3 sets of 500 mW transmitters (HC Timing, wiNode) to measure time and calculate speed on the hilltop in specific segment (segment 10). With this sensor-setup we could measure and log data for all skiers during the races and in the practical training session, with just one operator plotting in the bib number of the skier when passing. The position of the photocells-pairs together with altitude profile in the specific segment are visualized in **Figure 9**. Two specific measures were derived from the photocells: 1) instant speed after the acceleration-phase on the hilltop calculated by measuring the time in a 3 m segment ($\text{Speed}_{\text{PC2-PC1}}$, see **Figure 10** (right side) for picture of this 3 m segment at the hilltop), and 2) elapsed time from the speed measurement to the end of the downhill, i.e., approximately the time the skier was in tucked position ($\text{Time}_{\text{PC3-PC2}}$). In addition, a set of photocells (TC-Timer, Brower Timing Systems) was used to measure instant speed after the acceleration phase in a second segment (Segment 12) during the practical training session, and in the 20 meter flat- and uphill maximal speed tests.

3.7 Synchronization of sensor data from different sources

Paper 1 and 2: All sensor data (HR, $\dot{V}O_2$, TSI_{leg}, TSI_{arm}, cycle length, cycle rate, sub-technique, P_{cycle}, $\%P_{pole}$, $\%P_{ski}$, $\%P_{poleleft}$, $\%P_{poleright}$) were synchronized to a common master timeline and compound into one dataset with 1 Hz resolution before the means were calculated. Time offsets from the master timeline for treadmill speed and incline, HR, $\dot{V}O_2$ and NIRS data were manually recorded during the data collection. Time offsets for IMU-derived data (cycle length, cycle rate, sub-technique) were found based on identifying three synchronization jumps in the IMU data and on video. Reduction to 1 Hz resolution was done by calculating the mean for each second of data, which was the case for all types of data except the NIRS data where the mean 1 Hz values were calculated over three seconds to remove one second gaps resulting from the abovementioned filtering of the NIRS data.

Paper 3: Of the 57 skiers recruited, the 42 who finished within top 45 were included in our analyses. However, four of these had low-quality GNSS signals due to practical challenges (to short time in open air before start of the race), while three did not wear GNSS sensors as they were not among the 57 highest-ranked skier. Therefore, to include speed profiles from all top 45 skiers, we developed a method to synthesize data regarding position and time along the racecourse for those seven skiers with missing speed profiles. The model was derived using a deep learning approach (i.e., machine learning) with the official race timing (i.e., 17 points along the racecourse) of the 38 skiers with speed profiles of adequate quality as input data.

Paper 4: Data from the IMU (Physiolog 5) located on the chest and the IMU/GNSS (OptimumEye) sensor on the back were synchronized by cross correlating acceleration/gyroscope data recorded by the IMUs in both sensor systems. In addition, the HR data was correlated to the IMU data by cross correlation of the barometric sensor data in Physilog and the Garmin watch.

3.8 Statistical analyses

In all studies, data was tested for normality using a Shapiro–Wilk test in combination with visual inspection of data before being analyzed.

In Paper 1, all variables at low- and high-intensity sessions were compared using either paired *t* tests (data that met the assessment of normality) or a non-parametric Wilcoxon signed-rank test separately for low- and high-intensity data. In addition, a two-way repeated-measures analysis of variance was used to analyze the effect of segment and lap and their interactions on the different parameters and on the effect of intensity on time-dependent changes from Lap 1 (i.e., biomechanical and power) or Lap 2 (i.e., physiological) to Lap 7. When significant primary effects were found, post hoc analysis was performed to determine pairwise comparisons.

In Paper 2, one-way ANOVA with Tukey HSD post hoc test was used for analyzing differences in the measured physiological variables between the segments, with the first lap being excluded from the analysis. Correlations between performance ranking and the different variables were calculated using the Spearman product-moment correlation coefficient. In addition, Pearsons correlation coefficient between TTE and the different variables for the 9 skiers that completed the entire protocol without breaks (group 1) was compared.

In Paper 3, between-group comparisons for each segment and lap and between-lap comparisons for each segment and group were performed using one-way ANOVA. In cases of statistically significant differences between groups, Tukey post hoc analysis was conducted for comparison. Correlations between the start position and final rank were calculated using Spearman rank test. The quantitative data from the questionnaire, reported on a 10-point scale, were presented as median and interquartile range (IQR). Between-group differences for each item were examined using an independent sample Kruskal–Wallis *H* test, and, if statistical differences were found, then pairwise post hoc tests were performed to identify the differences. By contrast, the qualitative data were assessed and presented at the group level. Following a simplified thematic analysis, encoded thematic statements made by three or more skiers in the same group were summarized and are presented among the results.

Due to extensive statistical analyses with multiple comparisons in Paper 3, we decided to exclude some of the p-values. This was done for readability reasons and none of the excluded values were related to the main findings of this study. The remaining statistical findings are presented as following: Significant differences ($p < .05$) in average lap speed between neighboring performance-groups are shown with superscript in the speed profile figures for the full lap, for flat, downhill and uphill terrain, and for all of the specific segments. Statistical comparison of average speed between laps for the different performance groups are given in **Table 2**, while the overall trends for corresponding differences across terrain types and segments are presented in the text. For the quantitative data in the questionnaire, the p-values for the between-group comparisons are presented in **Table 3**, while the significant differences ($p < .05$) between groups using pairwise post hoc tests are visualized using superscript.

In Paper 4, an independent-sample *t*-test was used for assessing between-group differences in relative change of total race-time from Race 1 to Race 2 and for INT compared to CON. A paired t-test was used to compare HR, and Wilcoxon signed rank test to compare RPE from Race 1 to Race 2. A linear mixed model with lap number (Lap 1-3) and group/race-day (with a common baseline on Race 1) as fixed factors and skier id as a random factor was used to compare the relative change from Race 1 to Race 2 for INT compared to CON. Correlation between changes in performance for the skiers in INT from Race 1 to Race 2 with $\dot{V}O_{2peak}$ skate and different race-measures were calculated using Pearson correlation coefficient.

For all studies, the level of statistical significance was set at $\alpha = 0.05$. All statistical analyses except for the linear mixed model analysis were done using SPSS V26.0 (SPSS Inc., Chicago, IL, United States). For the linear mixed model analysis, Rstudio version "2021.09.1 Build 372" with the two libraries "lme4" and "foreign" was used.

4 Summary of results

The results presented here provide a summary of the results used in the original papers where the specific details are thoroughly described.

4.1 Low- vs. high-intensity XC skiing (Paper 1)

Both low- and high-intensity XC skiing on varying terrain induced large terrain-dependent physiological and biomechanical fluctuations (displayed in **Figure 15**). The specific size of the changes in the measured continuous physiological data (relative to the maximal levels) were heart rate (%HR, 17.7 vs. 12.2%-points), oxygen uptake (%$\dot{V}O_2$, 33.0 vs. 31.7%-points), and muscle oxygen saturation in the triceps brachii (TSI_{arm}, 23.9 vs. 33.4%-points) and vastus lateralis (TSI_{leg}, 12.6 vs. 24.3%-points). Also, for %$\dot{V}O_2$, the size of the terrain-dependent fluctuations was similar for low- and high-intensity ($p = 0.50$). Other similarities were that for both intensities the same sub-techniques were used in flat and moderate uphill terrain (**Figure 16**), and that there was a sub-technique dependency in the relative power contribution from poles and skis. The relative power contribution also exhibited a time-dependent shift in both intensities from Lap 1 to Lap 7 towards using gradually more ski power (6.6 vs. 7.8%-points, both $p < 0.01$) (**Figure 17**).

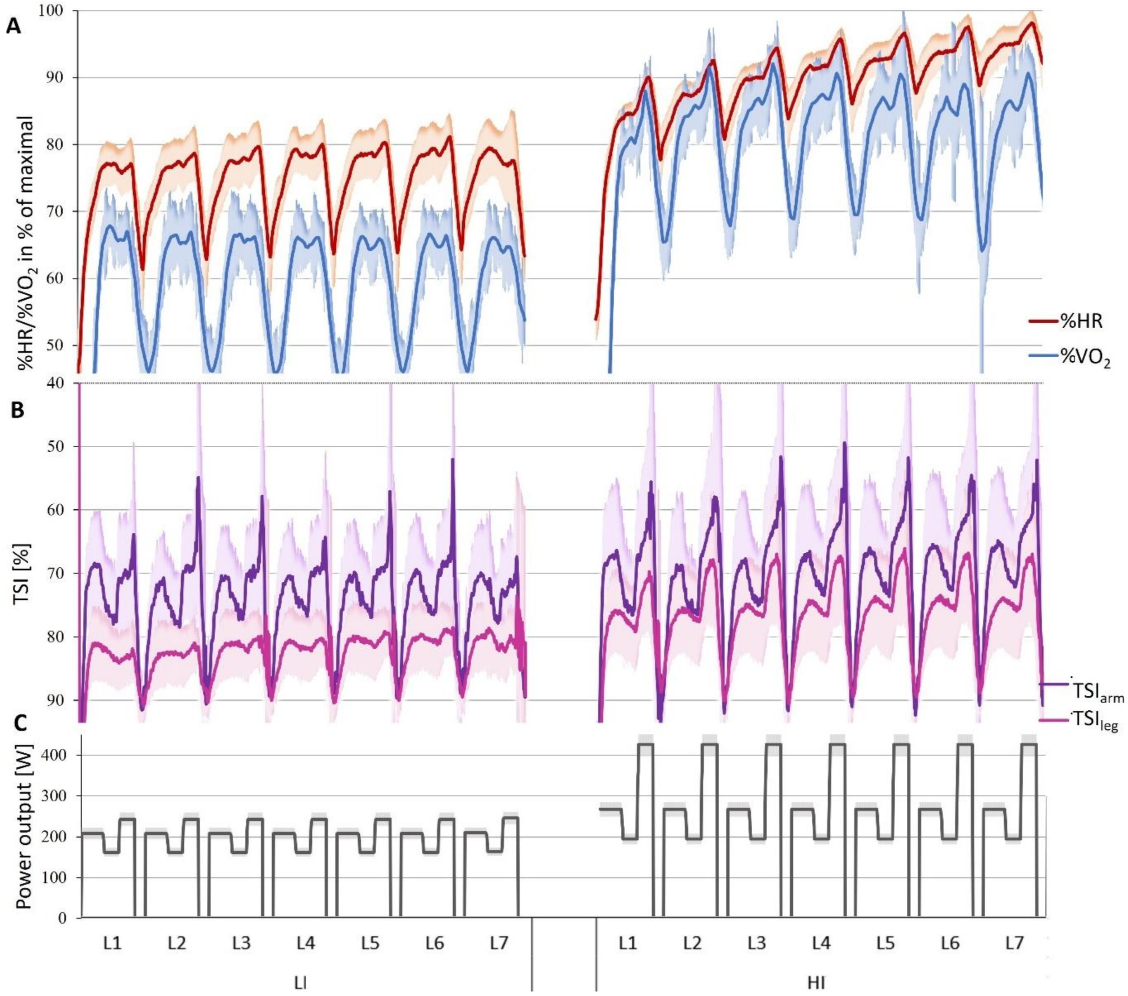


Figure 15 Relative heart rate (%HR) and relative oxygen uptake (%$\dot{V}O_2$) (30s moving average) (A), tissue saturation index for the vastus lateralis in the right leg (TSI_{leg}) and the long head of the triceps brachii in the right arm (TSI_{arm}) (B), and power output for the low-intensity (LI) and high-intensity (HI) sessions (M ± SD) with 1 Hz resolution (C). For TSI, the vertical axis is reversed. The figure is a replica of Figure 2 from Paper 1.

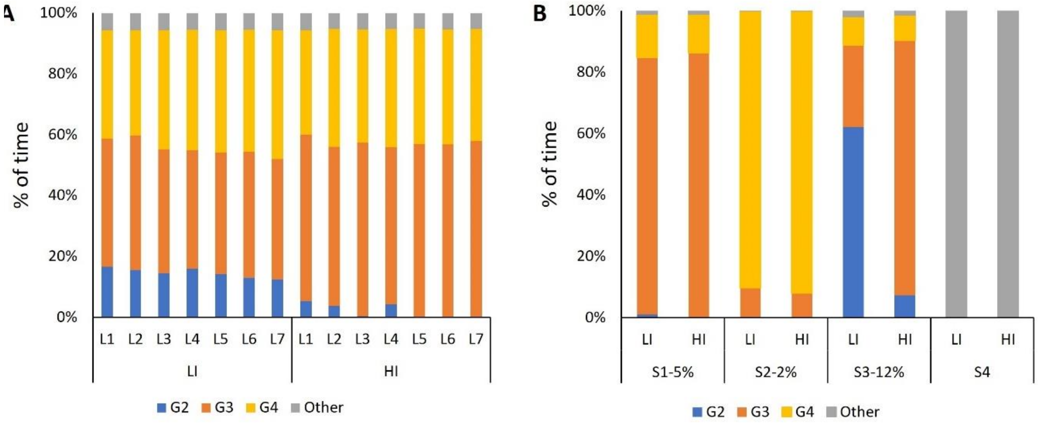


Figure 16 Distribution of sub-techniques, in percentage of time, A) as a function of lap (i.e., L1–L7) and B) as a function of segment (i.e., S1–S5), in the low-intensity (LI) and high-intensity (HI) sessions. The figure is a replica of Figure 4 from Paper 1.

In contrast to $\dot{V}O_2$, HR and TSI fluctuated less during high-intensity compared to low-intensity ($p < 0.01$) (**Figure 15**). During high-intensity HR displayed a time-dependent increase (mean, SD) from Lap 2 to Lap 7 (7.8 ± 1.1%-points). This drift was much larger than the corresponding values in low-intensity (2.3 ± 2.0%-points) ($p > 0.01$). Tissue-oxygen saturation shifted 2.4% points more for legs than arms from low- to high-intensity ($p > 0.05$). Regarding sub-technique distribution, which is displayed in **Figure 16**, 14.7% points more G3 on behalf of G2 was employed on the steepest uphill during high-intensity ($p < 0.05$). Within all sub-techniques, cycle length in the different sub-techniques increased two to three times more than cycle rate from low- to high-intensity in the same terrains, while the corresponding poling time decreased more than ski contact time (all $p > 0.05$) (**Figure 17**).

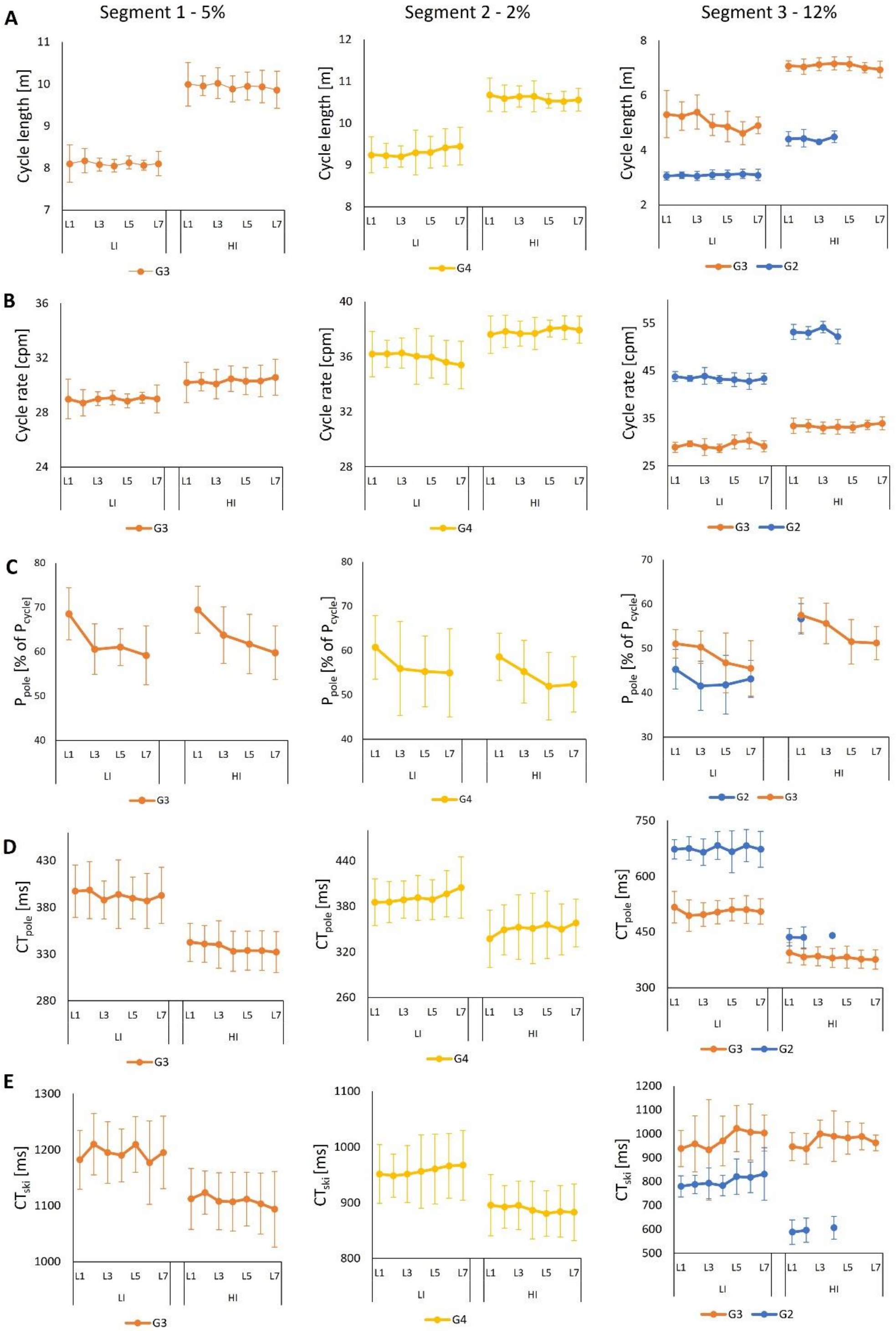


Figure 17 Cycle length (CL) (A), cycle rate (CR, in cycles per minute, cpm) (B), relative power contribution from poling (in % of total power for each cycle) (C), contact time for pole (CT_{pole}) (D), and contact time for ski (CT_{ski}) (E), all variables as a function of lap (i.e., L1–L7) during the low-intensity (LI) and high-intensity

(HI) sessions for each segment (*M* ± *SD*). Power from ski push-offs is given as $\%P_{ski} = 100\% - \%P_{pole}$. Power contribution was measured only for odd lap numbers and was not available for one of the skiers. If the skier spent less than 6 s on a particular sub-technique in one segment or lap, then it was excluded from analysis. During the HI sessions, G2 was used only by five skiers, one of whom was missing power data, hence the small sample. The figure is a replica of Figure 6 in Paper 1.

4.2 Simulated mass-start race (Paper 2)

Individual values, scatter plots and an overview of significant correlations between different measures (variables measured during the simulated mass-start and standard laboratory measures on a separate day in front of the race) are presented in **Table 5**, **Figure 18** and **Table 6**. Better performance ranking in the simulated mass-start was associated with higher $\dot{V}O_{2max}$ ($r = 0.68$) and gross efficiency ($r = 0.70$) (**Table 5** and **Table 6**). Also, higher performance was related to lower relative intensity [i.e., $\%HR_{max}$ ($r = 0.87$), % $\dot{V}O_{2max}$ ($r = 0.89$), and lower rating of perceived exertion ($r = 0.73$)] during the initial 21-min of the simulated mass-start (all p-values < 0.05) (**Figure 18** and **Table 6**). Accordingly, the ability to increase HR ($r = 0.76$) and $\dot{V}O_2$ ($r = 0.72$), beyond the corresponding values achieved during the initial 21-min, in the AOS correlated positively with performance (both $p < 0.05$) (**Figure 18**).

Sub-technique selection (distribution of G2 vs G3) during the main part of the mass-start (displayed in **Figure 19**) had a large correlation with performance, with the best-performing skiers using more G3 in the steepest uphill ($r = 0.69$, $p < 0.05$). Also, a trend was seen for the best performing skiers to use a longer cycle length during the all-out-sprint ($r = 0.52$, $p = 0.07$) (**Figure 18**). There was considerable subject-to-subject variation in power distribution from poles and skis, and between power produced by the left and right pole, but no significant correlations to performance.

Table 5 Physiological responses measured during the simulated mass-start (MS) and performance-determining variables measured during a separate day for the 13 individual skiers involved in this study. Values collected during the simulated mass-start are shown either for the initial part (IP) or after the all-out sprint (AOS). The table is a replica of Table 2 in Paper 2.

Performance			**MS – Mean values (Lap 1- Lap 3)**					**MS - After**		**MS - Peak values**				**Performance determining variables**				
Rank	**#B**	**TTE [s]**	**% HR_{Max}**	**% $\dot{V}O_{2max}$**	**$\dot{V}O_2$ [mmol/L·kg]**	**TSI_{arm} [%]**	**TSI_{leg} [%]**	**RPE [1-20]**	**BLa [mmol/L]**	**PeakHR [bpm]**		**Peak $\dot{V}O_2$ [mL/min kg]**		**$\dot{V}O_{2max}$ [mL/min ·kg]**	**Gross efficiency [%]**			
		AOS	**IP**	**IP**	**IP**	**IP**	**IP**	**IP**	**AOS**	**IP**	**AOS**	**IP**	**AOS**		**G2**	**G3**	**G4**	**OA**
1		130	83.5	74.2	54.7	59.4	61.3	16	10.5	182	193	70.5	74.3	73.8	17.7	15.9	12.7	15.4
2		119	85.1	73.2	53.4	43.8	51.9	17	7.2	184	190	71.7	73.4	73.0	17.4	15.1	12.6	15.0
3		101	87.3	78.2	53.2	45.2	55.3	16	14.3	171	177	69.4	71.0	68.1	17.0	14.9	12.0	14.7
4		91	90.2	74.9	55.0	45.0	58.1	18	12.0	199	202	73.1	71.7	73.4	17.3	15.4	13.0	15.2
5		82	88.0	73.2	53.0	58.5	64.6	15	8.7	187	189	67.6	67.7	72.5	16.9	14.8	12.9	14.9
6		74	88.8	76.7	56.8	36.0	51.4	17	12.9	203	202	72.7	71.4	74.0	16.4	14.5	12.1	14.4
7		65	88.5	79.3	51.3	47.8	57.3	20	10.2	191	189	66.1	61.8	64.8	17.4	14.9	12.8	15.0
8		60	90.6	78.0	53.4	50.1	63.3	19	12.0	193	194	66.1	65.0	68.5	17.3	15.0	12.9	15.1
9		47	89.0	79.4	53.2	65.3	69.7	17	11.8	193	189	68.6	62.9	67.0	17.1	15.1	12.7	15.0
10	1	50	93.7	81.6	58.8	54.4	65.2	20	16.7	202	200	72.6	69.1	72.0	15.8	14.0	11.7	13.8
11	2	62	92.6	83.8	54.7	42.4	46.5	19	18.7	195	196	69.3	63.3	65.3	16.7	14.6	12.1	14.3
12	2	47	91.5	86.6	55.2	63.8	55.6	19	15.1	201	196	67.3	61.1	63.8	16.5	14.5	12.0	14.4
13	3	66	91.1	82.9	56.2	51.0	54.1	20	12.0	189	190	70.9	70.6	67.8	16.2	14.0	12.1	14.1

Rank = ranking in the simulated mass-start, #B = number of 30 s breaks, TTE = time to exhaustion, HR = heart rate, HR_{max} = the highest measured heart rate, $\dot{V}O_2$= oxygen uptake, $\dot{V}O_{2max}$: The highest 30 s moving average (based on 10s mixing chamber values) during the incremental maximum test, TSI_{leg} = tissue saturation index for the vastus lateralis of the right leg, TSI_{arm} = tissue saturation index for the long head of the triceps brachii on the right arm, RPE = rate of perceived exhaustion, BLa = blood lactate concentration, Peak HR/ $\dot{V}O_2$= the highest measured HR/ $\dot{V}O_2$during the specified bout.

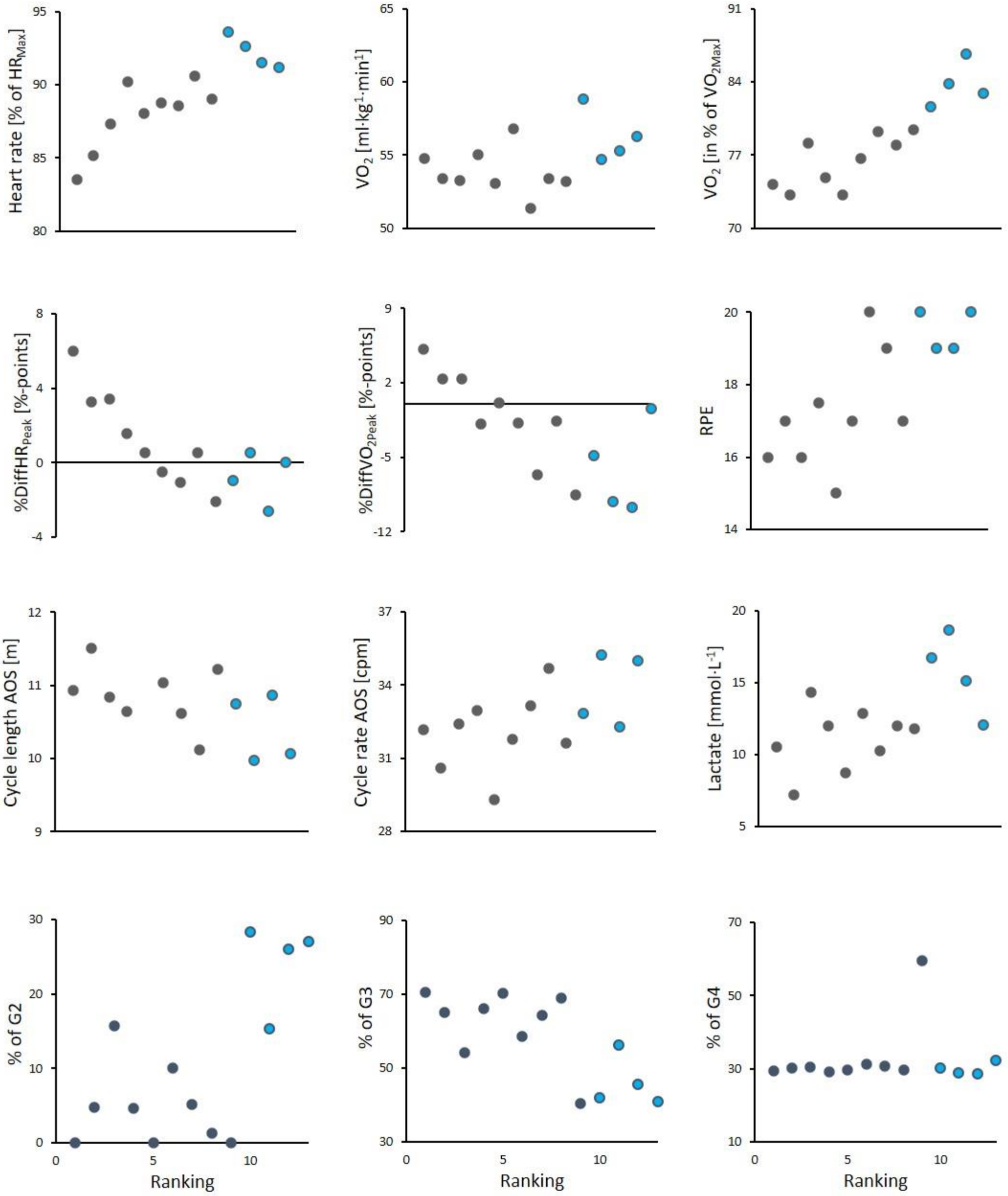


Figure 18 Scatter plots for athlete ranking in the simulated mass-start with the following parameters: mean values of heart rate (HR), oxygen uptake ($\dot{V}O_2$) and sub-technique selection during the first three laps of the simulated mass-start, as well as to the rate of perceived exhaustion (RPE) for the initial 21-min of the mass-start, cycle length and cycle rate during the first 3 steps of the incremental all-out sprint (AOS), blood lactate concentration (BLa) measured directly after the simulated mass-start and the difference between peak values of relative heart rate (%HR$_{max}$) and oxygen uptake (%$\dot{V}O_{2\ max}$) in the main part of the mass-start and the corresponding values during the AOS (%DiffHR$_{peak}$/%Diff $\dot{V}O_{2peak}$). The 9 skiers completing the entire protocol without breaks are shown with black color, while the 4 skiers who needed breaks are shown in blue color. The figure is a replica of Figure 5 in Paper 2.

Table 6 Spearman rank order correlation (RS) (for all 13 skiers) and Pearson correlation (RP) (for the 9 skiers who completed the entire protocol without breaks) between ranking (Spearman) respectively time to exhaustion (Pearsons) in the simulated mass-start (MS) and variables measured during the mass-start in addition to performance determining physiological variables (PDV) measured on a separate day. The mass-start is divided into the initial 21-min part and the all-out sprint (AOS). The table is a replica of Table 3 in Paper 2.

Correlation	**Protocol**	**Parameter**	**Laps**	**R_S**	**P_S**	**Laps**	***R_P***	***P_P***
				N=13	**N=13**		***N=9***	***N=9***
Extremely Large: $R_S > 0.9$	MS - Initial part	Peak HR [% of HRmax]	Lap 1-3	0.92	<0.001	All	*0.96*	*0.002*
Very large: R_S [0.70-0.89]	MS - Initial part	Mean $\dot{V}O_2$ [% of $\dot{V}O_2$max]	Lap 1-3	0.89	<0.001	All	*0.82*	*0.042*
	MS - Initial part	Mean HR [% of HR_{max}]	Lap 1-3	0.87	<0.001	All	*0.93*	*0.001*
	MS	$\%DiffHR_{Peak}$ (AOS- Initial part) [pp]	All	-0.76	0.001	All	*-0.97*	*<0.001*
	MS - Initial part	Rate of perceived exhaustion [1-20]	All	0.73	0.003	All	*0.69*	*0.192*
	PDV	Gross efficiency in G3	G3	0.72	0.006	G3	*0.74*	*0.126*
	MS	%Diff $\dot{V}O_2$peak (AOS-Initial part) [pp]	All	-0.72	0.001	All	*-0.94*	*0.001*
	MS – AOS	Peak $\dot{V}O_2$ [ml·/(kg·min)]	All	0.70	0.007	All	*0.88*	*0.016*
	PDV	Average gross efficiency	All	0.70	0.007	All	*0.57*	*0.576*
	PDV	Gross efficiency in G2	G2	0.70	0.008	G2	*0.65*	*0.265*
Large: R_S [0.50-0.69]	MS - Initial part	Use of G3 [%]	Lap 1-3	0.69	0.009	L1-3	*0.68*	*0.207*
	PDV	$\dot{V}O_{2max}$ [ml/(kg·min)]]	Max	0.68	0.010	Max	*0.78*	*0.082*
	MS – AOS	Blood lactate [mmol/·L]	After	-0.59	0.037	After	*-0.77*	*0.088*
	MS - Initial part	Use of G2 [%]	Lap 1-3	-0.56	0.048	L1-3	*-0.39*	*0.703*
	MS – AOS	Cycle rate in G3 [cycles per minute]	3 steps	-0.52	0.071	3 steps	*-0.52*	*0.480*
	MS – AOS	Cycle length in G3 [m]	3 steps	0.52	0.071	3 steps	*0.52*	*0.480*

HR = heart rate, HR_{max} = the highest value measured during all tests, $\dot{V}O_2$ = oxygen uptake, Peak HR/$\dot{V}O_2$ = the highest HR/$\dot{V}O_2$ measured during the specified bout, $\dot{V}O_{2max}$ = the highest 30s moving average measured (based on 10s mixing chamber values) during the incremental maximum test, Rs = Spearman rank order correlation coefficient, P_S = p-value for Spearman rank order correlation, $\%Diff\dot{V}O_{2peak}$ = the difference between peak values of relative oxygen uptake ($\%\dot{V}O_{2max}$) in the main part of the mass-start and during the AOS, $\%DiffHR_{peak}$ = the difference between peak values of relative heart rate ($\%HR_{max}$) in the main part of the mass-start and during the AOS, pp = percentage points, R_P = Pearson correlation coefficient, P_P = p-value for Pearson correlation coefficients.

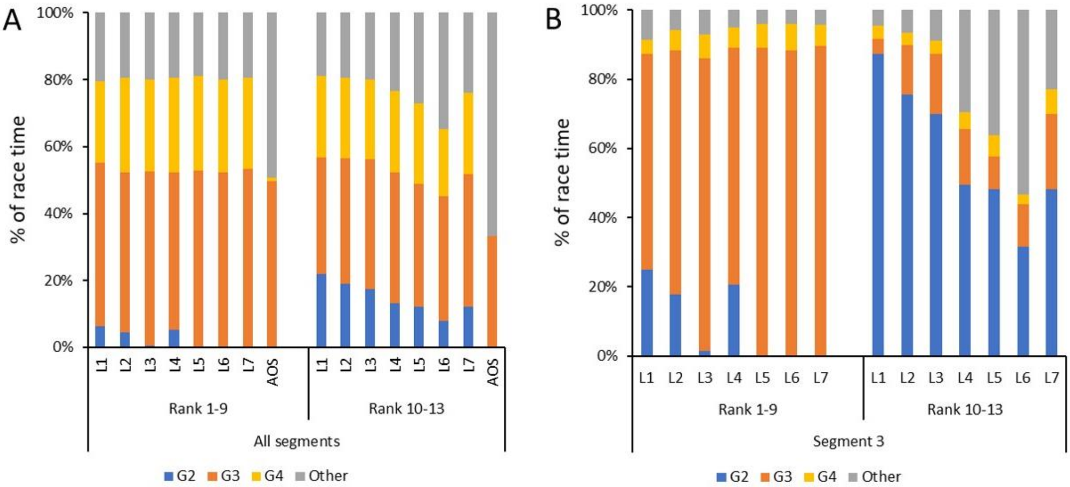


Figure 19 Distribution of sub-techniques [in % of time] for each of the seven 3-min laps (L) during the simulated mass-start, with the skiers divided into two groups: A) for all four segments in the initial 21-min and the all-out sprint (AOS) and B) for the steepest uphill. Skiers ranked 1-9 are those who were able to finish the entire protocol without requiring breaks and rank 10-13 consists of the 4 lowest ranked skiers that required one or more breaks to complete protocol. The figure is a replica of Figure 3 in Paper 2.

4.3 Mass-start competition (Paper 3)

In the mass-start competition, all skiers stayed together in one large pack until 2.3 km, in which lower-performing skiers gradually lost the leader pack and formed new, dynamic packs (illustrated in **Figure 20**) consisting of two to eight skiers. A picture of parts of the leader pack in segment 1 Lap 3 is shown in **Figure 21**.

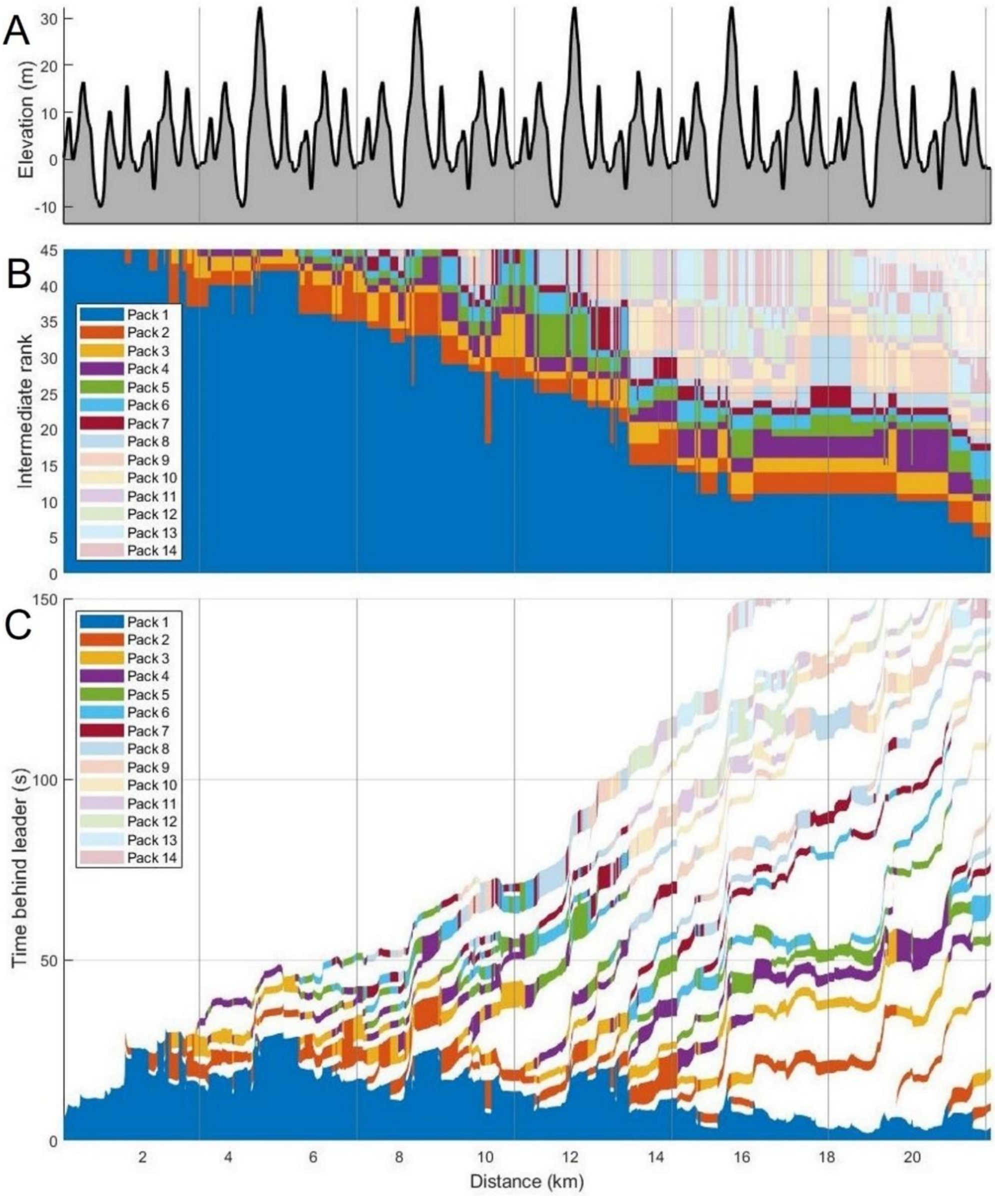


Figure 20 Elevation [m] (A), intermediate rank of skiers (B), and time [s] behind the current leader for each pack (C) as a function of distance [km] in a 21.8 km cross-country skiing mass-start competition. A pack of skiers including all consecutive skiers being less than 3 s apart and each pack is highlighted in different colors. The figure is a replica of Figure 5 in Paper 3.

Figure 21 Parts of the leader pack in segment 1, Lap 3. Photo: NTNU

Overall lap speed decreased after Lap 1 for all skiers and thereafter remained even for R1–10, while lap speed gradually decreased for the lower-performing groups (**Figure 22**). Skiers in R31–40, R21–30, and R11–20 fell back from the leader pack during Lap 3, Lap 4, and Lap 5, respectively. As revealed by the questionnaire, the skiers had the strategy of following the leader for as long as possible (median: 10, interquartile range: 4; on a scale from 1-10), even if they knew that they could not sustain the pace during all laps. Accordingly, the lower performing skiers had a more positive pacing pattern than the best performance group. The GNSS data showed that more than 60% of the time-loss relative to the leader pack occurred in sections of uphill terrain, average lap speed for each group as a function of lap speed for the different terrain types is displayed in **Figure 22.**

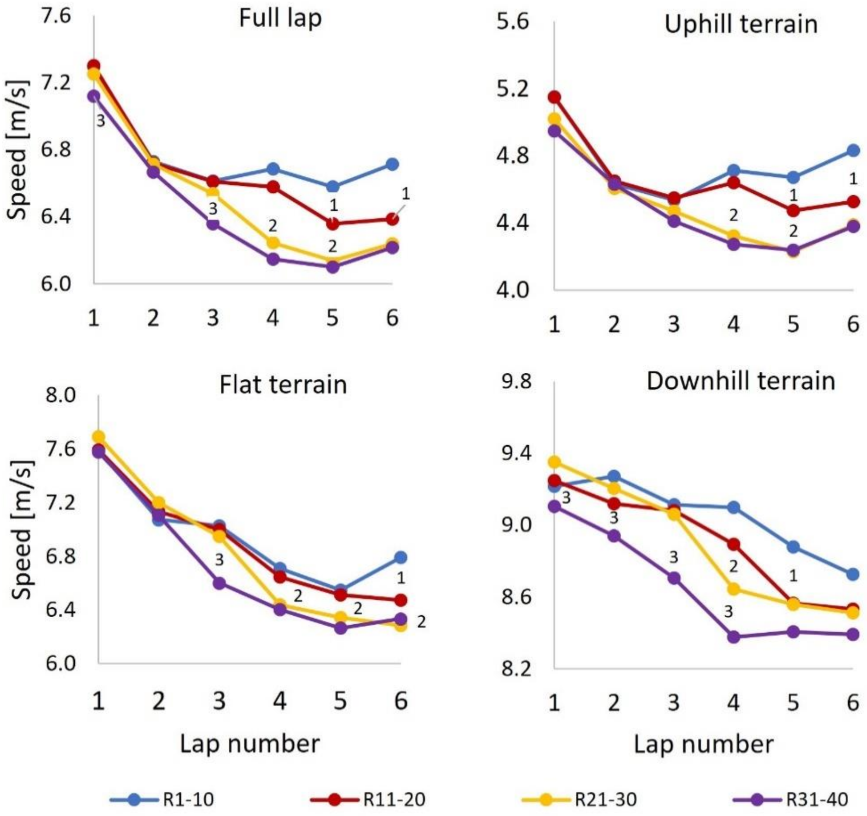


Figure 22 Average speed for full lap, uphill, flat, and downhill terrains as a function of lap-number for the performance-groups during a 21.8 km cross-country skiing mass-start competition. Note that Lap 1 was shorter than the other laps so speed for Lap 1 cannot be compared directly to speed on the following laps. Significant differences in corresponding speed-values between performance-groups are visualized in the figure. R1–10 (group 1) denotes ranks 1 to 10, R11–20 (group 2) ranks 11 to 20, R21–30 (group 3) ranks 21 to 30, and R31–40 (group 4) ranks 31 to 40. The notation "N" on the plots denotes that speed-value for current group was significantly different from group N. The figure is a replica of Figure 7 in Paper 3.

A considerable accordion effect occurred during the first half of the competition that led to additional decelerations and accelerations and a higher risk of incidents that disadvantaged skiers at the back of the pack (**Figure 23** and **Table 7**). Overall, 31% of the skiers reported incidents, but none were in R1–10 (**Table 7**). Overall, a high correlation emerged between starting position and final rank (n = 121, R = .88, p < .01).

Table 7 Summary of statements from the skiers (↑ illustrates the number of skiers) to the open questions in the questionnaire filled out after a 21.8-km mass-start competition in cross-country skiing, divided into different performance-groups. R1–10 denotes ranks 1 to 10, R11–20 ranks 11 to 20, R21–30 ranks 21 to 30, and R31–40 ranks 31 to 40).

R1-10	R11-20	R21-30	R31-40
Did you have any planned strategy that was not specifically addressed in the questionnaire?			
↑↑lie far forward in the pack to avoid the accordion effect ↑↑lie behind first part of the race and then try to speed up towards the end ↑overtake in flat /downhill terrain	↑↑lie far forward in the pack to avoid the accordion effect ↑overtake in flat /downhill terrain	↑↑↑ hang on to the leader pack as long as possible, but not stress with overtaking on the first laps ↑lie far forward in the pack to avoid the accordion effect ↑overtake in flat /downhill terrain	↑↑↑ hang on to the leader pack as long as possible, but not stress with overtaking on the first laps
What deviations did you have to the planned strategy, and why did it not go as planned?			
	↑↑lost time/positions due to an incident ↑↑was not in my best shape ↑bad skis	↑↑↑ lost the leader group earlier than planned ↑↑bad skis	↑↑↑↑↑↑↑↑↑ lost the leader group earlier than planned ↑↑↑↑was not in my best shape ↑↑↑ it was difficult to overtake ↑↑↑lost time/positions due to an incident ↑↑bad skis
Which advantages and/ or disadvantages did you experience when skiing close behind other skiers during the competition?			
Benefits: ↑↑↑↑↑↑ save energy due to less air resistance Disadvantages: ↑accordion effect first part of the race due to uneven speed	Benefits: ↑↑↑↑ save energy due to less air resistance Disadvantages: ↑↑↑ accordion effect first part of race due to incidents, stress, uneven speed, hilltops, coming into uphill segments, and narrow, technical terrain	Benefits: ↑↑↑↑ save energy due to less air resistance Disadvantages: ↑↑↑↑↑↑↑↑ accordion effect first part of race when the pack was large, particularly during two first laps, uneven speed, stress, risk of incidents	Benefits: ↑↑↑↑↑↑↑ save energy because of less air resistance Disadvantages: ↑↑↑↑↑ accordion effect first part of race due to uneven speed, too slow speed into uphill segments, incidents with skier in front
If you copied the movement pattern of the skier in front, which advantages and/ or disadvantages did you experience			
Benefits: ↑ more relaxed if skier in front had similar movement pattern as oneself ↑easier to stay close to the skier in front	Benefits: ↑↑↑↑ more relaxed/easier if skier in front had similar movement pattern as oneself Disadvantages: ↑↑↑ difficult if movement pattern is different to your own	Benefits: ↑↑↑easier to stay close to the skier in front Disadvantages: ↑↑↑ difficult if movement pattern is different to your own	Benefits: ↑↑↑↑↑ reduced risk of incidents in a large pack ↑↑↑easier to stay close to the skier in front Disadvantages: ↑↑↑↑difficult if movement pattern is different to own
Did you have any accidents during the competition, and if yes, which type of accident and how did it happen?)			
	↑↑↑ yes	↑↑↑↑↑ yes	↑↑↑↑ yes
Number of skiers that addressed the accordion effect in the open questions a) related to strategically avoiding it or b) experienced it.			
↑↑↑ strategically avoid	↑↑↑ experienced ↑strategically avoid	↑↑↑↑↑↑↑↑ experienced	↑↑↑↑ experienced

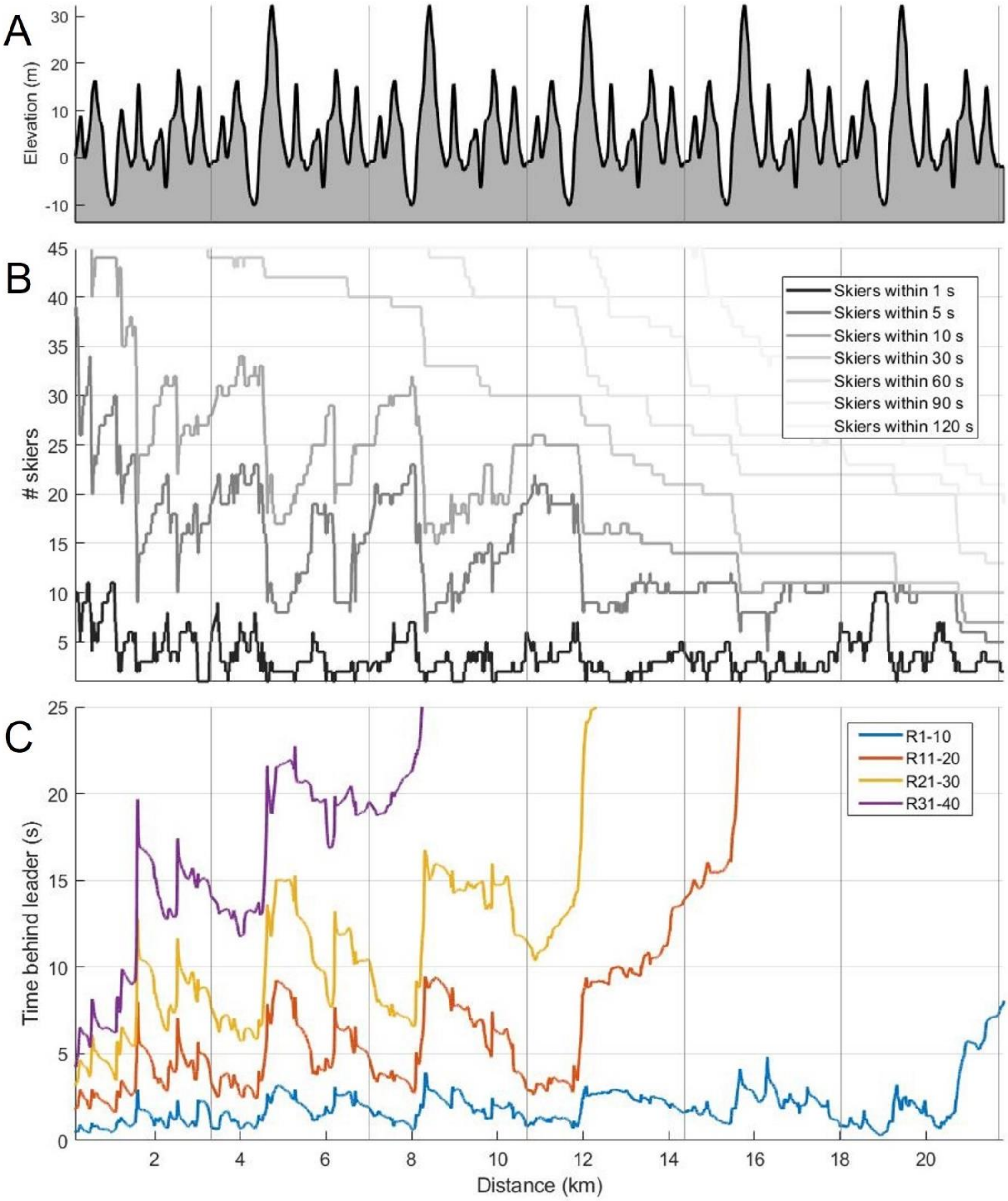


Figure 23 Elevation [m] (A), number of skiers within 1, 5, 10, 30, 60, 90 and 120 s from the current leader (B) and mean time behind the current leader for the different performance-groups (C) as a function of distance [km] in a 21.8 km cross-country skiing mass-start competition. Here, the accordion effect is clearly seen as fluctuating values from 0 to ~12 km particularly in relation to the longest uphill in for the two lines "skiers within 5 s" and "skiers within 10 s", and for the three lowest performance-groups (R11-20, R21-30, R31-40). R1–10 denotes ranks 1 to 10, R11–20 ranks 11 to 20, R21–30 ranks 21 to 30, and R31–40 ranks 31 to 40. The figure is a replica of Figure 6 in Paper 3.

Ultimately, top 10 skiers (R1–10) sprinted for the win during the last 1.2 km, in which 2.4 s separated the top five skiers, and a photo finish differentiated first from second place (**Figure 24** A and **Figure 25**).

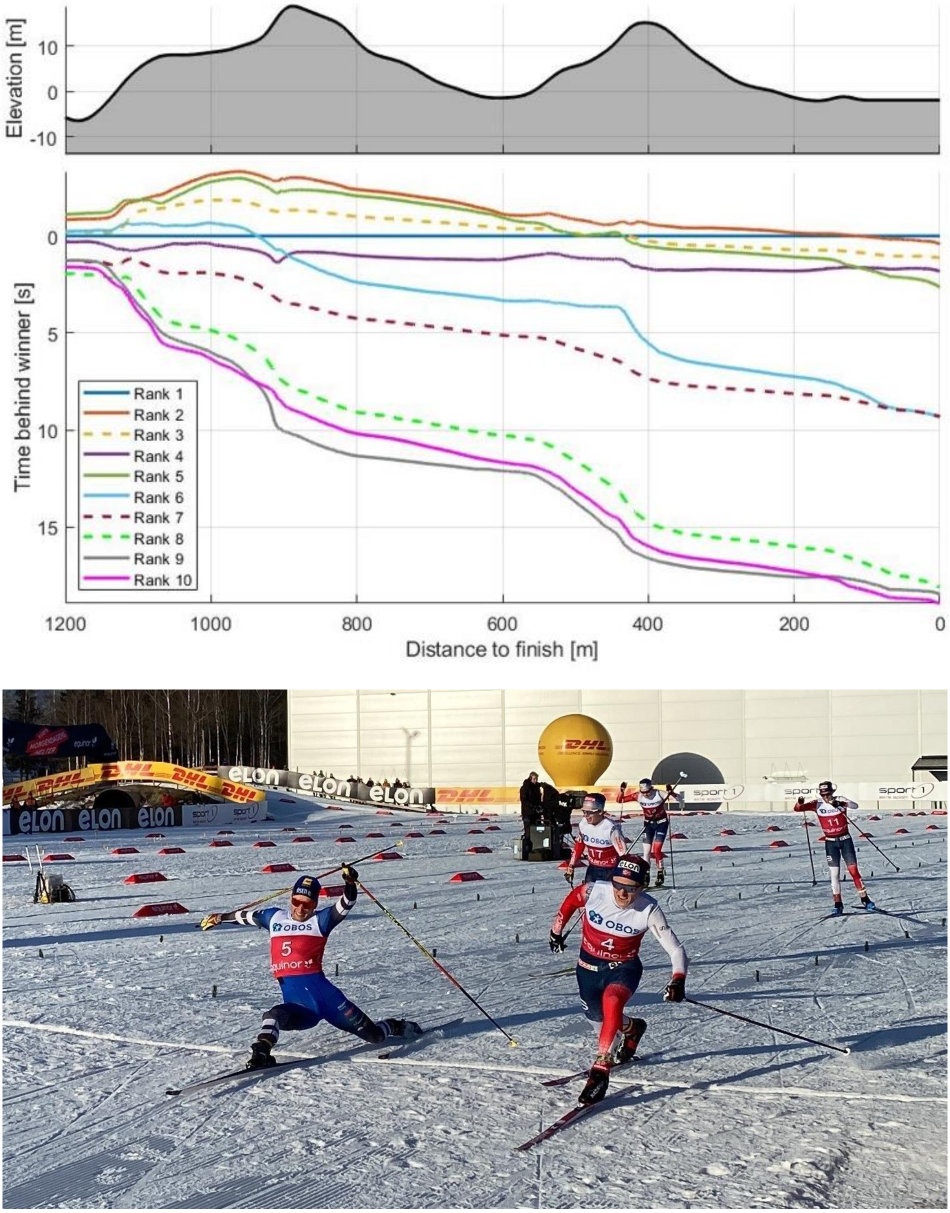


Figure 24 Time behind winner [s] for the top 10 skiers during the last 1.2 km of a 21.8 km mass-start competition (top) and picture of the two best skiers crossing the finish-line (bottom). Skiers with final ranks 3, 7 and 8 have synthetic speed profiles derived from a deep learning model described in detail in the methods. The figure is a replica of Figure 9 in Paper 3. Photo: NTNU.

Figure 25 The best performing skiers in Paper 3 immediately after the final sprint. Photo: NTNU.

4.4 Improving micro-pacing (Paper 4)

Initially, a high correlation was found between performance level of the skier (measured as used time in Race 1) and speed at the targeted hilltop (R = -0.57, p = .003) as well as time used in the subsequent downhill (R =0.80, p <.001), showing that higher performing skier initially were performing better at this specific micro-pacing. However, the initial speed at the hilltop was not linked to the speed reserves measured by 20 m maximal-flat (R = 0.38, p=.059) or -uphill speed (R = 0.35, p = .084).

From Race 1 to Race 2, the intervention group changed behavior and increased the total variation of chest acceleration (measured by *totVarAcc*) compared to the control group on all hilltops (P < .03) (**Figure 26** and **Table 8**). The continuous speed plot (**Figure 27**) displays similar speed in both groups in Race 1, while a substantial higher speed in INT versus CON occurs during the first part of the downhill and rest of the section in Race 2. The change in behavior lead to an increased speed on the hilltop and reduced time compared with the control group in a specifically targeted downhill segment (mean group difference: −0.55 s; 95% confidence interval [CI], −0.9 to −0.19 s; P = .003) (**Figure 27**). With all 3 laps included, INT improved in total 1.65 seconds (7.5%) compared with CON in this segment (segment 10). The intervention group also increased speed compared to the control group in overall time spent in downhill (−14.4 s; 95% CI, −21.4 to −7.4 s; P < .001) and flat terrain (−6.5 s; 95% CI, −11.0 to −1.9 s; P = .006). The continuous speed difference (mean lap value) between the intervention group and the control group according to the elevation profile and the time difference for each segment are displayed in **Figure 27** and **Figure 28**. There was a within-group variability in the intervention group, with a negative correlation between initial speed at the hill-top and the increase in speed from Race 1 to Race 2 (R = -0.56, p = .003), accordingly the skiers which had the lowest speed at the hilltop improved the most.

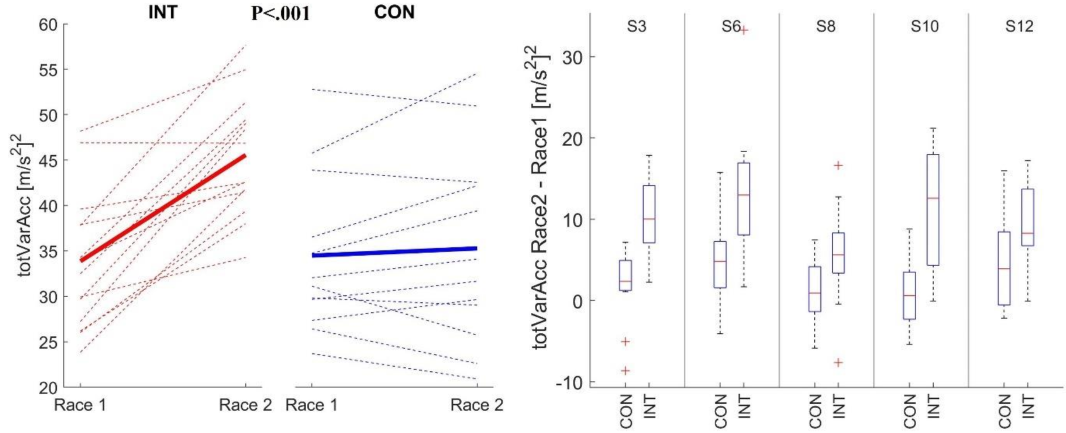


Figure 26 Left: Total variation of chest acceleration (*totVarAcc*) [(m/s^2)^2] on the hilltop of segment 10 (S10) for the intervention group (INT) and the control group (CON) for Race 1 and Race 2 (left graph), p-value for relative difference between groups is displayed. Relative *totVarAcc* [(m/s^2)^2] on the hilltops for Race 2 compared to Race 1 for INT and CON for all downhill segments (all p<.001) (right graph). The figure is a replica of Figure 4 in Paper 4.

Table 8 Relative change in "biomechanical intensity" on the hilltop (mean ± std) from Race 2 compared to Race 1 for the intervention group (INT) and control group (CON) for all downhill segments measured by three different metrics, *totVarAcc*, *AvFnet*, *PlayerLoad^{TM}*. See chapter 5.4.3 for information on *AvFnet*, *PlayerLoad^{TM}*.

Metric		***TotVarAcc* [(m/s^2)^2]**	***AvFnet* (filtered)**	***PlayerLoad* [·10^{-3}]**
Segment 3	CON	1.8 ± 4.6	10.3 ± 24.8	2.6 ± 2.6
	INT	10.4 ± 4.5	61.5 ± 37.4	3.7 ± 1.4
	P	***<0.001***	***<0.001***	***0.197***
Segment 6	CON	4.8 ± 5.5	24.9 ± 25.6	2.4 ± 1.9
	INT	12.8 ± 8.2	63.7 ± 51.1	3.6 ± 1.7
	P	***0.008***	***0.025***	***0.112***
Segment 8	CON	1.13 ± 3.8	-1.1 ± 21.8	1.7 ± 1.7
	INT	5.9 ± 6.0	21.1 ± 44.9	2.8 ± 1.2
	P	***0.026***	***0.131***	***0.072***
Segment 10	CON	0.8 ± 4.2	-2.9 ± 24.0	2.4 ± 2.2
	INT	11.7 ± 7.3	49.5 ± 37.4	4.7 ± 2.7
	P	***<0.001***	***<0.001***	***0.032***
Segment 12	CON	4.4 ± 5.6	20.6 ± 36.1	1.4 ± 2.9
	INT	9.5 ± 5.1	43.3 ± 36.6	2.7 ± 2.4
	P	**0.021**	**0.126**	**0.212**

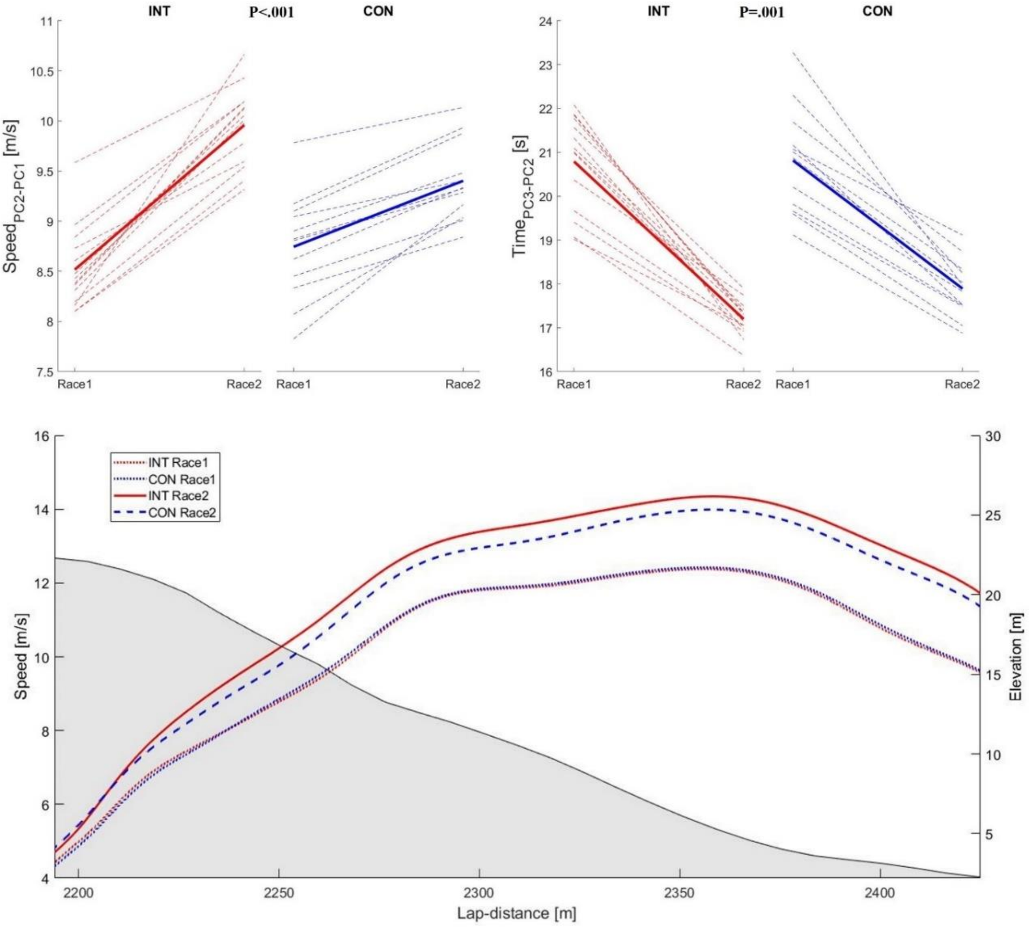


Figure 27 Downhill segment 10: Upper graphs: SpeedPC2-PC1 and TimePC2-PC1 [s] in Race 1 and Race 2 for the intervention-group (INT) and the control-group (CON), individual values printed in dotted-lines, and mean values in bold-lines. Lower graph: Continuous speed [m/s] (measured with GNSS) for Race 1 and Race 2 for INT and CON. The figure is a replica of Figure 2 in Paper 4.

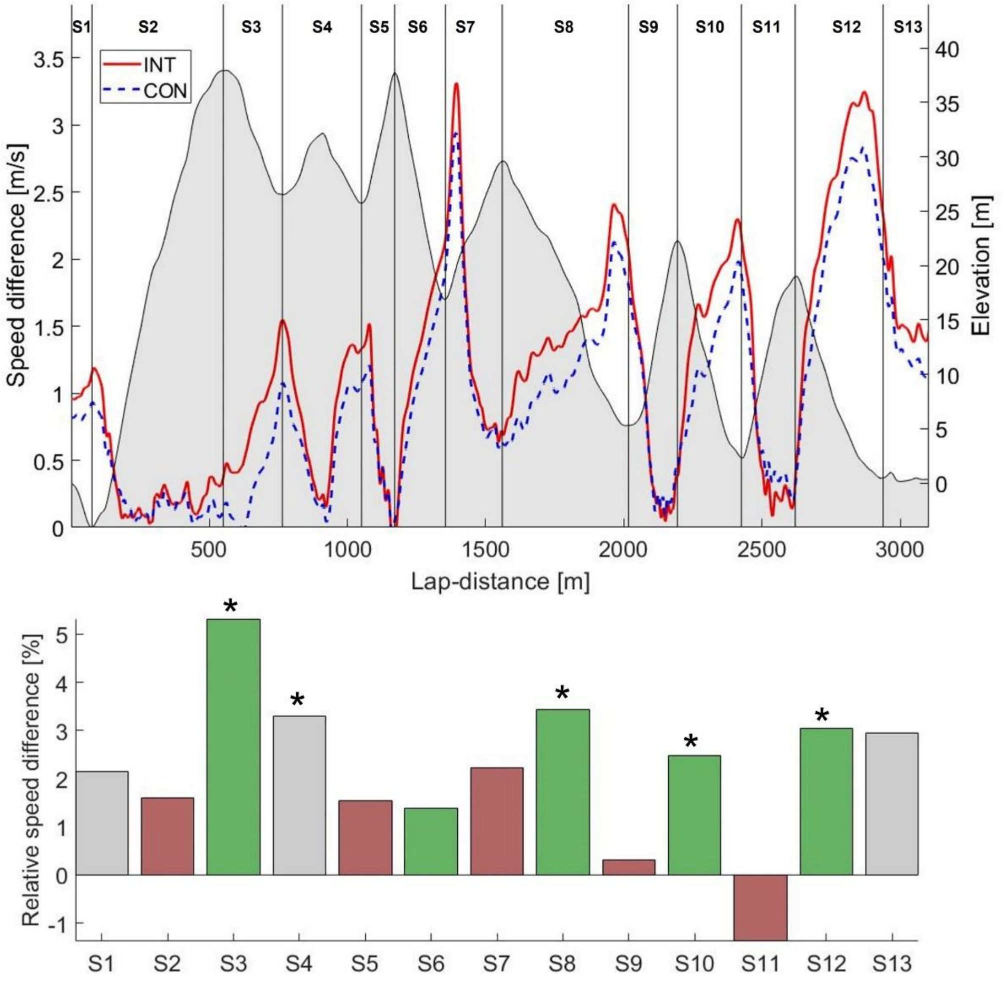


Figure 28 Mean speed difference [m/s] and elevation [m] for Race 2 compared to Race 1 as a function of lap-distance [m] for the intervention-group (INT) and the control-group (CON) (upper graph). Relative improvement in speed for each segment for INT compared to CON in Race 2 compared to Race 1 (lower graph). The figure is a replica of Figure 5 in Paper 4.

No significant between-groups differences were found for either overall time used in the uphill terrain (−9.3 s; 95% CI, −31.2 to 13.2 s; P = .426) or in total race time (−32.2 s; 95% CI, −100.2 to 35.9 s; P = .339). There was also no difference in the physiological intensity measures, HR and RPE, from Race 1 to Race 2 ((mean ± SD) - HR: INT -0.5 ± 1.0, CON -0.2 ± 0.2%-points of HR$_{max}$; RPE: INT -0.1 ± 0.8, CON -0.3 ± 0.7).

5 Discussion

5.1 Summary

The main objective of this thesis was to investigate physiological responses, movement techniques and their associations with training intensity and performance in cross-country skiing (XC) using sensor data, with a particular emphasis on mass-start competitions and the skating technique. The main findings are given below.

- Paper 1 showed several similarities between low- and high-intensity training on varying terrain. Both training intensities induced large terrain-dependent fluctuations in HR, $\dot{V}O_2$, and tissue oxygen saturation in arms and legs. In addition, power distribution generated by poles and skis depended on the sub-technique employed in a similar pattern both for low- and high-intensity, with a time-dependent shift towards gradually more power coming from the ski push-off from the start to the end of each session within all sub-techniques. Terrain-based fluctuations in $\dot{V}O_2$ were also similar at both intensities. However, there were also differences between intensities. HR fluctuated less at high-intensity and demonstrated a time-dependent increase (i.e., cardiovascular drift). In addition, G2 sub-technique was employed more than G3 on the steepest uphill section at low- than at high-intensity, while cycle length increased 2–3 times more than cycle rate, and CT_{pole} decreased more than CT_{ski} from low- to high-intensity when being compared in the same terrain.

- Paper 2 showed that performance in a simulated mass-start competition was associated with many of the same performance-determining factors as individual time trials, i.e., higher $\dot{V}O_{2max}$ and gross efficiency were associated with better mass-performance, uphill performance was found to be the most performance differencing terrain and the best skiers used skiing sub-techniques suited for higher speeds and adapted the associated macro parameters in steep terrain accordingly. However, the novelty of this study was that higher $\dot{V}O_{2max}$, and gross efficiency capacities seem to have different impact on mass-starts than shown for time-trials. Instead of using a superior $\dot{V}O_{2max}$ and gross efficiency to ski faster than lower-level peers throughout the entire race, which is normally the case for the best skiers during time-trials, our findings imply that skiers who score high on these performance determining variables could save energy and utilize their "reserves" better at the end of the race and in the final sprint. In Paper 3, it was found that the skiers moved in dynamic packs to benefit from drafting, and most of the included skiers had the strategy to follow the leader as long as possible. This led to a more positive pacing pattern for the lower-performing skiers that may have been sub-optimal for their performance. A considerable accordion effect occurred during the first half of the competition which led to additional decelerations and accelerations as well as a higher risk of incidents that disadvantaged skiers at the back of the pack. Accordingly, flexibility, speed resources and the ability to tolerate speed variations and avoid incidents are more important in mass-starts than in time trials. Summarized, the key factors determining mass-start performance were having an adequate starting position (i.e., set by performance level) and the ability to avoid incidents and disadvantages from the accordion effect, tolerate fluctuations in intensity, and maintain speed throughout the competition, as well as having well-developed final sprint abilities.

- Paper 4 explored how sensor data could be used to change behavior. It was found that the targeted training combined with video- and sensor-based feedback led to successful implementation of the terrain-specific micro-pacing strategy in XC skiing. This induced higher speed and reduced time in a specific targeted downhill segment, as well as overall downhill- and flat terrain, compared to a control group who performed similar training without any instructions or feedback.

- Methodologically, performance, physiological responses, and movement techniques for national level skiers using multiple sensors were explored during training and competition. Additionally, findings suggest that complementing outdoor studies with simulated indoor studies, conducted under controlled conditions using laboratory equipment, can yield data that enhances our understanding. In these studies, Global Navigation Satellite Systems (GNSS) sensors were used to measure speed and position both during training and competition and were shown to be a valuable tool to track performance and measure speed profiles. IMU data was used to validly classify skate sub-technique and corresponding macro- and micro-parameters both indoors and outdoors, and to estimate the total variation of chest acceleration (i.e., a measure for the biomechanical intensity). Physiological measurements were also explored, in which several challenges were observed. For example, simultaneous measurements of $\dot{V}$O2 and HR showed that HR has a significant intensity-depended drift and asymmetrical response to terrain that differs from the $\dot{V}$O2 response. Therefore, HR measurements must be interpreted with caution if it is used as a surrogate for $\dot{V}$O2 in the fluctuating terrain. The same applies to near infrared spectroscopy (NIRS) measurements, used to track variation in muscle oxygenation according to the terrain and sub-techniques, in which a large individual variability disqualifies this to be used as an absolute measure. In addition, this approach challenged the practical problem of measuring all parameters at the same time and successfully synchronizing them to a common timeline, which is required to provide complementary and integrative understanding.

5.2 Training for XC skiers

5.2.1 Physiological response to low- and high-intensity training

Both the low- and high-intensity sessions on varying terrain induced terrain-dependent fluctuations in %HR, %$\dot{V}O_2$ and tissue oxygen saturation (TSI), thereby exemplifying the interval-based cardiovascular and muscular loading during XC skiing, regardless of intensity. This major fluctuation in intensity is a unique property of XC skiing, in comparison to most other endurance sports, where loading is more consistent (Sandbakk et al., 2021). The terrain-based fluctuations in %$\dot{V}O_2$ were found to be similar at both intensities (32-33%-points), while this was not the case for %HR. The decrease in %HR during the simulated downhill was smaller and more delayed than the larger and more quickly responding decrease in %$\dot{V}O_2$. The difference between %$\dot{V}O_2$ and %HR response to downhills also depended on intensity, with the decrease in %HR during the simulated downhills in high-intensity being less pronounced than at low-intensity (18% vs 12%-points). This corroborates findings from other studies, which have shown that the fluctuation of %HR according to terrain depends on intensity (Haugnes et al., 2019a). During uphill, skiers often push the intensity up to, occasionally beyond their $\dot{V}O_{2max,}$-level. The resulting oxygen deficit may lead to a reduced and delayed HR recovery (Solli et al., 2018; Gløersen and Gilgien, 2021). In low-intensity conditions, the skiers reached an average of 81% of HR_{max} and 76% of $\dot{V}O_{2max}$. However, during high-intensity conditions, the skiers surpassed 98% of both HR_{max} and $\dot{V}O_{2max}$, thereby leading to a subsequent oxygen deficit. Additionally, we observed a significant time-dependent drift in %HR (i.e., cardiovascular drift) during high-intensity exercise (~7%), which differed from the drift noted during low-intensity exercise (~2%). In contrast, the %$\dot{V}O_2$-response to the fluctuating terrain remained consistent throughout both low- and high-intensity sessions, except during Lap 1. In this instance, %$\dot{V}O_2$ was lower due to skiers starting from a relaxed condition. This is the first study that examines simultaneous HR and $\dot{V}O_2$ responses to XC skiing in varying terrain as a function of intensity. Collectively, our findings have significant implications for interpreting %HR during training and competitions at low- and high-intensities, as it is often employed as a real-time proxy for %$\dot{V}O_2$ during non-steady-state exercises such as XC skiing (Bolger et al., 2015; Solli et al., 2018; Haugnes et al., 2019a).

Like HR- and $\dot{V}O_2$-values, the TSI-values also fluctuated according to the terrain both at low- and high-intensity, with only slight delays in kinetics similar to findings from a study measuring oxygen saturation in working muscles (i.e., biceps brachii, triceps brachii, latissimus dorsi, and vastus lateralis) during successive upper-body sprints (Sandbakk et al., 2015b). Further on, TSI values for both arms and legs decreased significantly from low- to high-intensity as expected. However, the terrain-dependent fluctuations in TSI in the arms differed from the corresponding measurements in the legs and were not associated with the amount of power generated by the arms versus legs. That finding aligns with results from a recent case study during a long-term competition in double poling, in which TSI measures for the triceps brachii showed larger terrain-based fluctuations than for the vastus lateralis (Stöggl and Born, 2021). Our findings thereby indicate that the desaturation of the muscles depends more on whole-body stress (i.e. %HR and $\%\dot{V}O_2$) than the contribution from specific muscles, as previously suggested (Im et al., 2001). Mean values for TSI_{arm} were less than mean values for TSI_{leg} at both low- and high-intensity, which indicates less oxygen saturation in the arms than the legs at both intensities. This aligns with the power data that showed that the skiers adapt their technique to the workload by generating more power from poling than ski push offs at both intensities. This also correlates with two other studies in which elite skiers performed diagonal stride (Björklund et al., 2010) or double poling (Stöggl et al., 2013). Interestingly, the mean value for TSI_{leg} decreased more than for TSI_{arm} from low- to high-intensity, thereby indicating that for XC skiing the muscular load of the arms seem to be more independent of the overall intensity than the muscular load of the legs. That finding may have implications for understanding the specific muscular workload of low-intensity training on varying terrain, by indicating that skiers can experience a high muscular training load in the arms at low-intensity as well as at high-intensity. However, muscle deoxygenation in XC skiing is a complex topic and studies focusing more specifically on this issue are needed to conclude. This could be studied during controlled conditions on a treadmill with a similar sensor setup, but with another protocol with several steady state levels with increasing intensity (speed) for the same incline/sub-techniques.

5.2.2 Sub-technique selection, macro- and micro-parameters

We found that the skiers selected G4 in the relatively flat terrain (2% incline) and G3 in moderate uphill terrain (5% incline) irrespective of the intensity. However, during the steep uphill (12% incline) the skiers used more G3 and less G2 during high-intensity than at low-intensity. Accordingly, our findings indicate that skiers apply the same sub-techniques regardless of training intensity across flat, and moderately uphill terrain (which is naturally also the case for downhill terrain), but they use different sub-techniques in the steep uphill terrain. Although our findings are limited to specific speed and inclines, this study contributes significantly to the literature since sub-technique distribution as a function of varying terrain and intensity in the skate style has not been studied before. Our findings align with speed and incline-thresholds in **Figure 4** (Losnegard, 2019), though the skiers in our study used G3 during a slightly steeper inclines than stated in the figure.

Both macro- and micro-kinematic variables were highly dependent on sub-technique and incline, consistent with findings from previous studies (Nilsson et al., 2004; Stöggl and Müller, 2009; Sandbakk et al., 2012a). Both cycle length and cycle rate increased with higher intensity and speed, with cycle length increasing 2–3 times more than cycle rate from low to high-intensity within most sub-techniques. This observation contrasts with earlier research, where cycle rate was identified as the primary driver of speed at moderate to high speeds (Millet et al., 1998; Nilsson et al., 2004). However, it aligns with more recent findings that both cycle rate and cycle length drive speed (Sandbakk et al., 2012a; Sandbakk et al., 2015a), and that cycle length increases more than cycle rate as a function of speed (Sandbakk et al., 2012a). Possible explanations include the evolving technique and requirements for XC skiing over the years and the varying skill levels of the skiers studied. It has been proposed that the high work rates required for modern elite skiing at higher speeds cannot be achieved without increasing both cycle rate and length (Lindinger et al., 2009a; Sandbakk et al., 2012a). Moreover, studies on double poling have shown that a lower enforced frequency corresponds to lower HR, oxygen uptake, and blood lactate concentration, potentially enhancing gross efficiency and improving performance (Holmberg et al., 2006; Lindinger and Holmberg, 2011). Given that G3 and G4 share similar arm movements with double poling, this principle is likely applicable to these sub-techniques as well.

Along with the increase in cycle length and cycle rate with speed, contact time for poles and skis (CT_{pole} and CT_{ski}) decreased from low- to high-intensity across all sub-techniques. While the decrease in CT_{pole} is expected, as it is highly dependent on speed, CT_{ski} could be maintained at higher speeds by angling the skis more forward. However, future studies should consider dividing CT_{ski} into push-off and gliding (i.e., no push-off) times to provide a more nuanced understanding of how these variables change with intensity. This approach was conducted in a study using G3 at two different inclines and intensities, revealing that glide time increases with speed, while ski push-off time remains relatively constant (Sandbakk et al., 2012a). For both poles and skis, relative contact times ($\%CT_{pole}$, $\%CT_{ski}$) also decreased from low- to high-intensity, though this change was significantly smaller than the absolute change in contact time (CT_{pole}, CT_{ski}). This can be explained by the fact that while skiers power output is higher during high-intensity sessions, they are compelled to produce this power over shorter periods, resulting in longer relative recovery times within a cycle (Sandbakk et al., 2012a). This pattern implies altered muscle contraction dynamics from low- to high-intensity and necessitates that skiers possess the ability to produce the required power within a short timeframe.

5.2.3 Power distribution between upper and lower body

Overall, in Paper 1 it was found that the skiers adapt their technique to the workload by generating more power from poling than ski push offs during both low- and high-intensity session. The distribution of pole and ski power in this protocol with set speeds and inclines seems less dependent on intensity than on sub-technique and thus incline. At low-intensity, for example, we found more ski than pole power in the steep uphill ascent, both in G2 and G3, whereas more pole power was produced in G3 during the moderate incline. In addition, the findings related to G3, with more pole power produced at lower inclines, align with results from a study of the distribution of power generated by the arms and legs during double poling (Danielsen et al., 2019). Here the authors found that double poling at 12% incline required less power from the arms than at a 5% incline, partly due to less advantageous working conditions for the arms with shorter poling times and a reduced angle between the arms and the ground at steeper uphill. Because G3 and double poling have synchronized, highly similar arm movements, the same could be assumed to apply to our findings—that is, that less advantageous working conditions for the arms are causing the reduced power contribution from the arms at higher inclines. However, those aspects require further examination by using a specifically designed experimental setup.

Independent of intensity and sub-technique, the relative pole and ski power distribution gradually changed, with a higher contribution of ski power toward the end of the session. The change in power distribution could have been done intentionally to save the legs toward the end, or else because the skiers became more fatigued in the upper than in the lower body and therefore gradually generated more ski power. That compromise between generating arm (i.e., pole) and leg (i.e., ski) propulsion during skiing likely depends on individual resources and on how skiers pace their arms and legs, an aspect that requires more attention in future research. However, the change in power distribution did not influence cycle length or cycle rate, which varied according to incline, speed, and sub-technique used but showed the same pattern within each sub-technique for all laps.

5.2.4 Micro-pacing over hilltops

XC skiers employ a variable pacing pattern with higher metabolic rates and power production during uphill than flat and downhill terrain. To further improve performance, refining XC skiers micro-pacing strategy, by adjustments of speed and/or transitions between sub-techniques within or between terrain sections, can be beneficial. Based on practical training with elite skiers and findings in the literature we hypothesized that increasing speed over specific hilltops to save time in the subsequent downhill without reducing speed in other parts of the track could improve XC skiing performance (Paper 4). In this study, the intervention group improved performance significantly more than the control group in the specific targeted downhill segment. The improvement was explained by more active poling and leg kicks (verified by measurements of the total variance of the chest acceleration) leading to increased speed and reduced time in the subsequent downhill. Furthermore, this is in line with previous findings, where instant speed during the acceleration phase at the hilltops have been shown to be related to time spent in the subsequent downhill (Ihalainen et al., 2020).

A high correlation was found between performance level of the skier (measured as used time in Race 1) and speed at the targeted hilltop as well as time used in the subsequent downhill, showing that higher performing skier initially were better at this specific micro-pacing. However, the initial speed at the hilltop was not linked to the speed reserves measured by 20 m maximal flat, or uphill speed. Also, the increased speed at the hilltop from the intervention was not linked to the skiers maximal aerobic power ($\dot{V}O_{2peak}$ skate measured in the laboratory) or the speed reserves (measured by a 20 m speed tests in front of the races), implying that the increase in performance occurred independent of these factors. Furthermore, the skiers with lower initial speed in the specific downhill segment during Race 1, improved their speed more than the skiers with higher speed, and the skiers with longer race-time in Race 1 improved overall race-time more than the faster skiers. Accordingly, our finding of improved speed over the target hilltop and subsequent downhill in INT indicates that individual strengths and weaknesses should provide the point of departure for developing targeted micro-pacing strategies, which is further supported by a recent study showing that XC skiers with a fast-start pacing pattern increased overall performance by reducing the speed in the first uphill (Losnegard et al., 2022).

Interestingly, the results could also be generalized to other downhill segments. Although the skiers only received specific feedback and performed practical training in two of the five downhill terrain segments, the intervention group improved performance compared to the control group in four of the five downhill segments, leading to significant improvements in overall downhill terrain. The lack of improvement in one of the downhills (segment 6) was likely due to the segment being relatively short and steep, limiting the amount of time to save from this micro-pacing strategy. Overall, this indicates that the training was sufficient to adopt better micro-pacing strategies in other downhills than those used in the practical training session. However, an important issue is that the skiers should be aware of where it is, and where it is not, beneficial to use this strategy. The most important situations are where the skier maintains speed for a longer duration (in time), meaning where there is a longer distance before the skier has the possibility to accelerate again. This technique is probably more effective in classic style compared to skating, due to the restrictions in sidewise gliding. In skating it is easier to compensate for a lower speed at the hilltop with active propulsion during the downhill when the slope is flat enough for “free-skating” (G6). Another point to consider is also that the gained speed can be carried into the next uphill section and enable higher speed in that section. Situations when it is not beneficial to use this strategy are when the hilltop is too steep, or the downhills are technically difficult with sharp curves.

No effect on the intervention was found in the overall uphill terrain or in the physiological responses, HR and RPE, indicating that the skiers used the same overall effort in both races. The mean improvement in race time was higher for the intervention group than the control group, however, the difference was not statistically significant, meaning that no effects of the intervention on overall race performance were found. Since previous studies have shown that uphill terrain is the most performance-differentiating terrain in XC skiing (Andersson et al., 2010; Sandbakk et al., 2011a; Bolger et al., 2015; Sandbakk et al., 2016b) it is likely that individual performance differences from Race 1 to Race 2 in the uphill terrain “masked” the improvements observed in the downhill sections in this relatively heterogenous group of skiers. This is also supported by the recent study investigating micro-pacing strategies during a distance XC skiing competition, showing that skiers with shorter race-times skied faster in specific parts of the uphills (Staunton et al., 2022b). In addition, although the study design (i.e., balanced groups both according to performance and starting time) took account for a change in snow and weather conditions, it is likely that the non-linear changes in the external conditions during the race-days have impacted our results. Also, since the skiers with lower initial speed in the specific downhill segment improved their speed more than the skiers with higher speed, the overall result may have been different if this criterion had been used to divide the skiers in the two groups.

Although the observed improvements in downhill terrain in the intervention group did not significantly influence the overall competition performance, downhill performance might be crucial when the margins between skiers are small (Spencer et al., 2014; Ihalainen et al., 2020), which is common in XC skiing (Spencer et al., 2014). In our study, INT improved 14.6 s/2.9% in downhill and 6.5 s/2.7% in flat terrain compared to CON, corresponding to 1.0% and 0.4% of the total competition time respectively. This improvement is higher than the smallest worthwhile improvement (defined as the required improvement in performance that could significantly influence the results) calculated to be 0.3-0.4% (Spencer et al., 2014). In the mass-start competition described in Paper 3, where many competitors were on a homogenous level and the margins are very small, using this strategy along the race could have contributed to be able to stay-in-the group, less fatigue and consequently be better fit for the final sprint.

5.2.5 Practical implications

Even though XC skiing competitions are performed at high-intensity, with high-intensity sessions regarded as a key stimulus in the development of XC skiers, most of the training is performed as low- intensity sessions (Sandbakk and Holmberg, 2017). Low-intensity training is traditionally regarded beneficial as it allows a large volume of training by keeping the degree of accumulated fatigue low. Still, training specificity is of importance since the stimuli provided during training should improve race-specific capacities. A practical implementation of this is to perform most low-intensity sessions on less strenuous terrain to enable the use of the same sub-techniques with relatively little effort. Furthermore, it seems important to prioritize training in G3 at relatively high speeds during steep uphill ascents as part of high-intensity or sprint sessions, since this skill is challenging to practice while keeping the intensity low.

Several similarities were found in physiological and biomechanical responses between low- and high-intensity training on varying terrain, which indicates that many of the demands that are important for XC skiing competition can also be trained during low-intensity, especially in the less strenuous terrain (Paper 1). This includes adapting the body to be able to work hard when required and quickly recover when the demand in workload is low, balance the amount of power from ski push offs and poling efficiently and sustainable in the different sub-techniques and train different movement patterns with the adequate sub-technique related to flat and moderate uphill terrain. In this setting, one of the findings from the mass-start competition (Paper 3) was that skiers that could easily adopt sub-technique and cycle rate/length to the skier in front had an advantage compared to less flexible skiers. Accordingly, it can be beneficial to train on different combinations of cycle rate/length to develop a high spectrum of temporal patterns within the different sub-techniques to tolerate a variability in rhythm. This can be done during low- intensity training, without a high cost. Furthermore, to simulate competition-relevant cycle lengths the skiers could include periods in their low-intensity training during which they intentionally aim to ski with a lower cycle rate than normal, as done in other sports, including road cycling (Aasvold et al., 2019). Such low-frequency training may be particularly relevant in relatively flat (or gentle downhill) terrain where cycle length has been shown as the main driver of increased speed. This training may also be beneficial for increasing gross efficiency since higher performing skiers have shown to use longer cycle length than lower performing skiers (Zoppirolli et al., 2020). It has also been shown that lower cycle rate (and as a consequence longer cycle length) has lower gross efficiency, %HR and blood lactate concentration compared with higher cycle rates (Lindinger and Holmberg, 2011; Leirdal et al., 2013) and that gross efficiency is highly reduced when the skiers were forced to use a higher cycle rate (+10 strokes/min) than preferred.

Since XC skiing is such a technically demanding sport, the skiers can also practice different technical aspects like downhill turns and position, and relevant micro-pacing, for example how to accelerate over the hilltop to gain time in the sub-sequent downhill, while maintaining low-intensity (Paper 4). Our study shows that high-level XC skiers can reduce the time spent in downhill and flat terrain by implementing a terrain specific micro-pacing strategy using video- and sensor-based feedback in a time-efficient manner. The combination of a theoretical lecture, including video and speed analysis highlighting the potential to gain seconds, and objective feedback directly after each trial during a training session, seems to have created an effective learning process. Furthermore, this methodology can likely be used to develop better micro-pacing skills in other parts of the course or by focusing on technical aspects like the choice of sub-technique or regulation of cycle length and rate. Nevertheless, it is important that the coaches and skiers carefully analyze racecourses and evaluate where there are the most seconds to gain from such strategies. Furthermore, the time spent training on this must also be weighed against improving other factors of importance for performance in XC skiing (eg, high aerobic power and efficient technique).

All these findings build upon the scientific evidence explaining why elite XC who compete at high-intensity, still have a good effect of training large volumes as low-intensity.

5.3 Mass-start competitions

5.3.1 Pacing in mass-start competitions

The GNSS data from the mass-start competition showed that average lap speed decreased from Lap 1 to Lap 2 and thereafter remained fairly constant among the best-performing skiers, whereas lower-performing skiers gradually decreased their speed throughout the competition, particularly in uphill terrain. As revealed by the questionnaire, the skiers had adopted the strategy of following the leader for as long as possible (median: 10, interquartile range: 4 on a scale from 1-10), even if they knew that they could not sustain the pace during all laps. A similar strategy has also been described in mass-start competitions in other endurance sports such as running and triathlon (Vleck et al., 2008; Hanley, 2015), but never in a mass-start XC skiing competition. For the lower-performing skiers, this strategy led to positive pacing, and they most likely had higher relative intensity during the first part of the competition. Such positive pacing patterns may be disadvantages compared to more even pacing strategies that have shown to be beneficial in individual time trials in XC skiing (Losnegard et al., 2016; Stöggl et al., 2018a; Losnegard et al., 2021).

In the outdoor mass-start competition, although lap speed in the leader pack remained fairly constant during Laps 2–6, the speed temporarily increased during some of the segments in the second half of the competition. Such pacing was also commented on in the questionnaire by a skier in the best performance group (R1–10): “Laps 4 and 5 were hard as expected, but the first part of the last lap was easier. I couldn’t keep up when the speed increased again”. Accordingly, the ability to ski at high speed over time and tolerate rapid variations in speed and intensity during the last part of the competition distinguished the highest-performing skiers from their lower-performing peers. The same trends appeared in pacing and tactics during track-and-field world-level competitions, when data across distances ranging from 800 m to 10 km were examined (Hettinga et al., 2019). Here the medalists were able to maintain high speed throughout the entire competition and accelerate near the end of the race, whereas lower-finishing athletes were only able to keep the pace temporarily before slowing down or being unable to accelerate as much as the medalists (Hettinga et al., 2019).

The physiological responses to pacing patterns in varying terrain was explored in the indoor simulated mass-start competition (Paper 2). During the main part of the simulated mass-start, which had variable incline and same speed for all skiers (i.e., simulating the “stay-in-the-group” condition), the best skiers had lower %$\dot{V}O_2$ and %HR and became less fatigued than the lower performing skiers. Accordingly, they showed a better ability to increase $\dot{V}O_2$ and HR with gradually increasing speed during the all-out-sprint. In fact, in the all-out-sprint the lower-performing skiers were not able to reach % $\dot{V}O_2$- or %HR-values above those achieved during the main part of the mass-start, which may explain their limited ability to reach high speeds during the end of the “race”. Specifically, the skiers ranked 6–13 in this study reached similar or higher HR and/or $\dot{V}O_2$ values during the main part compared to the all-out-sprint, while the HR and $\dot{V}O_2$ values for the 1-5 ranked skiers were significantly higher during the all-out-sprint compared to the main part. Although XC skiing includes higher effort uphill and downregulation of effort in downhills (Gløersen et al., 2018b; Karlsson et al., 2018; Stöggl et al., 2018a), it seems important for skiers to work below a certain threshold also in the hardest parts (uphills). This allows them to recover sufficiently in the subsequent downhills as studied in a 15 km simulated time-trial race where elite skiers repeatedly attained substantial oxygen deficits in uphill segments (Gløersen et al., 2020). Here the deficits for each segment were relatively small compared to their maximal accumulated oxygen deficit (MAOD), and within a level that could rapidly be recovered. Still, the total accumulated race O_2 deficit was several times the maximal accumulated oxygen deficit, suggesting that the ability to repeatedly use and recover the energy is an important energy contribution for an optimally paced race as well as a performance indicator. This was also supported by a study comparing elite and lower-level skiers alternating between 3 min at 90% and 6 min at 70% of % $\dot{V}O_{2max}$ (Björklund et al., 2011). Here it was showed that the lower-level skiers were less able to reduce blood lactate concentration during the 70% intervals compared to elite skiers, even though there was no significant difference in blood lactate concentration between the two groups after the first 90% interval. These findings support the results presented here, illustrated by how the positive pacing strategies (involuntary) applied by the lower performing skiers in the main part limits their ability to recover and reach their full potential when sprinting at the end of the protocol.

In sum, the requirement of tolerating high speed over time in addition to brief fluctuations in intensity, both due to fluctuation terrain and temporary increases in speed independent of the terrain, is unique for XC skiing compared to most other endurance sports and particularly pronounced in mass-start competitions. It may therefore be beneficial to include such features in training sessions, i.e., to practice variable intensities during long tempo sessions and train final-sprint abilities in a fatigued state.

5.3.2 Pack Formation

Skiing in packs is a unique possibility and feature of mass-start competitions and may provide energetic benefits due to reduced aerodynamic drag and ski–snow friction while skiing behind others. For example, in road cycling the aerodynamic drag can be as low as 50% of the drag for an isolated rider at the same speed when moving in a large peloton of cyclists (Blocken et al., 2018). Due to lower speed in XC skiing compared to cycling, the effect of reduced drag is expected to be lower but may still play a significant role (Ainegren et al., 2022). In the XC mass-start competition (Paper 3) it was found that the skiers preferred to race together in packs, mainly to benefit from the drafting effect. The GNSS data showed that all included skiers stayed together in a large pack until 2.3 km, at which point lower-performing skiers gradually lost the leader pack and formed new, dynamic packs of two to eight skiers. This was confirmed by responses to the questionnaire, here the skiers wrote that they preferred to ski together in packs and saving energy by reducing aerodynamic drag was reported to be the key motivation. Accordingly, the dynamic pack formation observed in this competition is consistent with what previously has been shown during mass-starts in other endurance sport events such as running and triathlons (Vleck et al., 2008; Hanley, 2015).

To benefit from the drafting effect, it is important to stay as close as possible to the preceding athlete. As shown in cycling (Blocken et al., 2013) and speed skating (Elfmark et al., 2019) a synchronized motion is necessary to keep a short separation from the athlete in front. Also, wind tunnel measurements from speed skating suggest that the reduction in aerodynamic drag is greater if competitors move in synchronized than in unsynchronized movements. Additionally, in XC skiing, placing the skis in the same tracks as the skier in front lowers the ski–snow friction for the skier behind. This implies that a synchronized motion is beneficial in XC skiing. However, this may be difficult, since XC skiing movements are performed in sub-techniques, and the skiers may have different preferences for sub-technique selection and corresponding cyclic movement patterns in the constantly changing terrain. Further, sub-technique selection and rhythm in both skate and classic style have been known to vary between skiers with different performance levels (Marsland et al., 2017) (Seeberg et al., 2017; Solli et al., 2018; Tjønnås et al., 2019), but also within groups of skiers with similar level (Paper 1, Paper 2 (Marsland et al., 2017; Solli et al., 2018). In Paper 2, the relatively homogenous group of national level skiers were found to prefer the same sub-technique in flat and relatively slow incline uphill, while in the steepest uphill, the best skiers used more G3 compared to G2 than the less-performing skiers. In addition, we found that the cycle rate/length during the all-out sprint was a performance differentiating factor where the best skiers used a longer cycle length and lower cycle rate than the weaker performing skiers at the same speed. We also found that the corresponding preferred rhythm (i.e., cycle length and cycle rate combination) had a standard deviation between skiers of 3-5% during high-intensity and 3-9% in low-intensity in the different sub-techniques. About the same variance was seen in the micro-parameters, CT_{pole} and CT_{ski}. The questionnaire in the mass-start study (Paper 3) confirms that several skiers perceived it as advantageous to follow the cyclic patterns of the skier in front if they had similar patterns to their own. However, the questionnaire revealed that this potential advantage was perceived as being stressful if the technical pattern of the preceding skier was different from the preferred rhythm. Taken together, since skiers have different preferences in sub-technique selection and rhythm and it is beneficial to move with the same technical pattern as the preceding skier, mass-start competitions favor flexible XC skiers that can ski efficiently in the terrain independent of sub-technique and cycle rate. Therefore, it may be beneficial to include such flexibility in the training, as also discussed elsewhere.

In Paper 3, it was revealed that there were also challenges with moving in large packs, particularly for skiers far behind in the pack. One of these disadvantages was the reported challenges with overtaking other skiers during the competition. In this race the final rank of 80% of the top 45 skiers was within ± 15 places of their starting position. Therefore, a starting position in the front of the pack may be crucial for the final rank. However, because the starting position was based on previous performances (i.e., FIS distance points), we do not know how much of the variance can be explained by difficulties in overtaking competitors and thus cannot establish any cause–effect relationship. Also, the difficulty of overtaking will be highly dependent on the course and will be more difficult in skating than in classic style due to the angle of the skis. Our finding is similar to trends in a World Cup mass-start race in XC mountain biking, in which the size of the starting field was like that in our study (i.e., approx. 100–250 starters). Here it was found that the finishing position depended heavily on starting position and most competitors did not vary in finishing position compared with their starting position by more than ± 15 places among elite men, and ± 10 places among elite women

(Macdermid and Morton, 2012). In view of those results, future research should examine the advantages and disadvantages of starting position and whether changes in the starting order or restrictions on course layout are necessary for fair competition.

Another disadvantage of moving in packs was that a considerable accordion effect occurred for lower-performing skiers during the first half of the competition. Although the accordion effect previously has been described in other sports, i.e., in road cycling (Trenchard, 2010; Blocken et al., 2018), our study is the first to reveal it in XC skiing. Similar to overtaking, the accordion effect depends on the racecourse, including the elevation profile, the width of the track and the number and type of turns, along with the number of skiers who start together, the snow conditions, and the skiers performance level. This racecourse had several steep, short uphill segments, as well as some difficult sharp turns and many skiers at the same performance level. Thus, there was likely a particularly large accordion effect in the competition, which the skiers described as “large”, “mad” and “extreme”. The best skiers (R1–10 skiers) reported to have a strategy to avoid the accordion effect by staying in the front of the leader pack (approximately top 10). In contrast, skiers in lower-performing groups reported disadvantages such as uneven speed, forced to have too low speed into the uphills and stressful skiing. They also had a relatively high risk of accidents, especially in the first part of the competition and when approaching uphill terrain, over hilltops, and in narrow, technical terrain. Moreover, the quotes from the skiers were confirmed by the GNSS data which showed accelerations and deaccelerations for the skiers in the back of the pack. To summarize, 31% of the skiers reported being involved in at least one incident during the competition, but none of them were in the highest-performing group (R1–10). The ability to avoid incidents therefore seems to be crucial for the XC skiers final position. Additionally, the accordion effect prompted mental stress and additional decelerations and accelerations for skiers in the back of the pack. This effect was not studied in our simulated mass-start, so we do not know the physiological response to this. However, it likely had a considerable additional energetic cost accompanied by the risk of premature fatigue. Therefore, future research should explore the additional energetic cost and physiological response to the disadvantages from the accordion effect such as uneven speed with multiple decelerations and accelerations in controlled environments. Nevertheless, due to the disadvantages of the accordion effect in mass-start races, skiers should make an effort to reduce those disadvantages as much as possible. For the best performing skiers, this could be done by staying far ahead in the group or, for lower-performing skiers, to leave the leader pack early and ski at their own pace in the first part of the competition and have more energy to advance in the second half of the competition when the accordion effect is minimal.

5.3.3 Performance in different terrain

As consistently observed in time trials (Andersson et al., 2010; Sandbakk et al., 2011a; Bolger et al., 2015; Stöggl et al., 2018a), uphill was found to be the most performance-determining terrain, both in in the indoor simulated mass-start in XC skiing (Paper 2) and in the mass-start competition on snow (Paper 3). The GNSS data showed that over 60% of the timeloss for the lower performance-groups compared to the best group was in the uphill terrain (Paper 3). Further on, in the indoor study, the lower performing-skiers that needed breaks decided to take those breaks in the steepest uphills (Paper 2).

There are several factors that may contribute to the importance of uphill terrain. Firstly, since the racecourses in XC skiing consist of approximately one-third ascending, one-third flat and one-third descending terrain (International Ski and Snowboard Federation (FIS), 2022) and the workload and thereby time used is higher in uphills, over 50% of the time is spent in this terrain. Secondly, due to the higher workload in the uphills, skiers with higher endurance will have a benefit in this terrain. This is confirmed by findings in Paper 2 where the best skiers had higher $\%\dot{V}O_{2max}$ than the lower performing skiers. Thirdly, it was also found that the best skiers had higher efficiency in the different sub-techniques, and that sub-technique selection in the steepest uphill had a very large correlation with performance, where the best skiers used more G3 at the expense of G2. Actually, the sub-technique selection in the steepest uphill divided the skiers into two groups, where only the best skiers utilized G3. In contrast, the 3 skiers who only used G2 in this section were in the group of lower-performing skiers requiring one or more breaks. This means that the lower performing skiers were not able to utilize G3 in the steepest terrain either due to lower efficiency and technical ability, lower endurance capacity, lower strength, or a combination of those. This finding aligns with results from a sprint time trial where the sprint skiing performance was related to uphill performance, and greater use of the G3 technique (Andersson et al., 2010). It also corresponds with conclusions from two recent reviews (Stöggl et al., 2018a; Zoppirolli et al., 2020), where performance was linked to the ability to maintain speed in a specific section of a race. In our study, the skiers used the same speed in all similar terrain sections, but in line with the differences in relative intensity during the mass-start, sub-technique selection was also clearly differentiating performance levels.

There was also between-group speed-differences in the downhill terrain in the mass-start competition, here R31–40 had a constantly lower average speed than all other groups in all laps (Paper 3). Several possible factors might have contributed to the difference in downhill performance; more incidents for lower-ranked skiers, less technical and tactical downhill skills, and the accordion effect in the main pack. In addition, skiers in R31–40 alone reported having less competitive skis than their peers. Furthermore, this could also be due to less optimal micro-pacing, i.e., for example the lack of acceleration over hilltops as shown in a recent study (Ihalainen et al., 2020). This study investigated micro-pacing strategies during a classical sprint time trial and found that instant speed during the acceleration phase over hilltops was significantly correlated to the time spent in the subsequent downhill section and that performance in downhill terrain influenced the overall performance. Additionally, in Paper 4 we found that the performance level of the skier correlated with speed at the targeted hilltop and time in the subsequent downhill. It is therefore possible that the lower-performing skiers to a lower degree than the higher-performing skiers used this strategy in the mass-start race, and that this contributed to lower speed in the downhill terrain. They may also have been hindered to use this technique by the other skiers in the leader pack, and in the first part of the study in combination with the accordion effect.

In contrast to uphill and downhill terrain, speed along flat terrain was similar in all groups except in the final lap, where R1–10 had higher speed than all other groups in the final sprint (Paper 3). This aligns with results from the simulated mass-start (Paper 2), here both the performance and the sub-technique selection were similar in flat- and medium uphill terrain (Paper 2). In conclusion, uphill performance, as previously shown in time trials, is also a major determinant of performance in the skating-style mass-start competitions.

5.3.4 Final sprint abilities

In difference to time trials, mass-start are head-to-head competitions, in which the winner is the first person to cross the finish line. In our mass-start competition the final sprint began 1.2 km before the finish line, here all skiers in the best performing group (R1–10) were together in the leader pack. At this point the current leader (R2) accelerated using G2 on a short uphill climb (segment 11), and three skiers immediately lost contact with the pack. R2 continued this high-intensity towards the finish line and the other skiers followed to their ability. In the end, five skiers approached the final 400 m and the outcome of the competition was decided in an all-out-sprint. At the finish line, 2.4 s separated the top five skiers, and a photo finish was needed to differentiate first (R1) from second place (R2). Accordingly, many competitors demonstrated a relatively similar performance level, and only marginal time differences distinguished them.

In the indoor study, the simulated all-out-sprint was performed directly after the main part at medium incline (5%) with increasing speed every 15 s. It was found that the ability to perform well during this sprint largely correlated with both gross efficiency and $\dot{V}O_{2max}$, which allowed better skiers to work on a lower relative intensity during the initial part of the simulated mass-start. This was also supported by the measures of intensity during the simulated stay-in-the-group condition, where a large correlation between performance and during the simulated mass-start (%HR_{max}, % $\dot{V}O_{2max}$ and

RPE) was present. This implies that a combination of higher aerobic energy delivery capacity and better efficiency allows the best performing skiers to start the final sprint with less accumulation of fatigue and/or more anaerobic energy left. Also, in individual time trial competitions both $\dot{V}O_{2max}$ and gross efficiency have been shown to differentiate skiers and to allow skiers to utilize a higher aerobic power during time-trial competitions (Sandbakk and Holmberg, 2017). However, the novelty of our study is that these capacities seem to play a different role in mass-starts than shown for time-trials. Instead of using a superior $\dot{V}O_{2max}$ and gross efficiency to increase speed, which is normally the case during time-trials, our findings in the simulated mass-start imply that skiers who score high on these performance-determining variables can save energy during the race and are therefore able to utilize their “reserves” better at the end. Independent of endurance capacities, the ability to generate a high maximal speed will also be important for the final sprint, however this was not feasible to measure in our mass-start studies.

Coinciding with less tiredness and higher aerobic power during the all-out-sprint, which was performed in G3, better performing skiers also showed the ability to concurrently produce longer cycle length and thereby have a lower cycle rate at the set speed in all-out-sprint than their lower-performing peers. Cycle length has been identified as a performance indicator in several studies, while cycle rate is to a lower degree associated with performance (Stöggl et al., 2018a; Zoppirolli et al., 2020). However, no previous studies have examined temporal patterns in a final sprint where skiers had various degrees of accumulated fatigue as often occurring during a mass-start race.

In outdoor mass-starts competitions tactical considerations are also highly important. In our race R2 pushed speed the whole final sprint and the winner laid behind until the last meter of the race. The questionnaire revealed that this was a tactical assessment from this skier: “Had to go to the front a little earlier than planned on the last lap to avoid the sprinters getting a cheap entry to the last km”. Different skiers have different characteristics, for example skiers that often perform well in sprint competitions have been found to have higher BMI and lower $\dot{V}O_{2max}$ than skiers that often perform well in long distance time trials (Losnegard and Hallén, 2014). For the skiers that do not have the best sprint abilities it is always a trade-off between laying behind and thereby saving energy or pushing high speed in order for the best sprinters (which often have less endurance) to lose the leader pack. It might have been another outcome of the race if the R2 skier had not been pushing the speed so early in the race, then maybe another skier with better sprint abilities in the best performing group (R1-10) would have won. Either way a consequence is that the ability to generate high speed at crucial moments, and especially in the final sprint in a fatigued condition, is an essential factor of performance in mass-start XC skiing competitions, as also highlighted earlier in this thesis and in other papers (Sandbakk and Holmberg, 2017; Losnegard, 2019; Seeberg et al., 2021).

5.4 Utilizing sensors in outdoor XC skiing

5.4.1 Speed, location and altitude

In XC skiing, measuring and tracking performance can be challenging due to variations in external conditions, such as temperature, humidity, snow conditions, varying snow/ski friction, and hilly tracks. Unlike sports like running and cycling that can use speed or power meters for performance comparison and pacing calculations, these methods are not directly applicable in XC skiing. However, GNSS sensors can be used by skiers to compare performance during a race by evaluating the same segment across laps. It is also possible to compare performance with other skiers using a similar approach. Additionally, efforts have been made to measure power in XC skiing (Moxnes et al., 2013; 2014; Gløersen et al., 2018b). Power measurement provides in principle a more objective way to assess performance, enabling reasonable accuracy for comparisons across tracks and partially across snow conditions, especially in uphill sections. However, accurate elevation profiling requires the use of differential GNSS due to the vertical inaccuracy of GNSS. While Garmin integrates power measurements into their sports watches for XC skiing, the accuracy of this measure has not been documented.

In this thesis, GNSS devices were utilized to measure speed and position during training and competition, serving as a valuable tool for tracking performance and capturing speed profiles. For the two time trials conducted in the intervention study (Paper 4), a validated GNSS device called Optimey5 from Catapult was employed, as previously documented in a similar setting (Gløersen et al., 2018a). Additionally, in this study, photocells were incorporated in a specific segment (segment 10) alongside the GNSS sensor to measure speed at the hilltop and time during the subsequent downhill section. Therefore, for this particular segment, the GNSS measurements were solely utilized to provide supplementary information about speed development within the segment. This information was presented during the theoretical training session, where the speed development of each skier was compared to that of the best-performing skier. In summary, while differences in downhill performance among athletes could likely be observed using GNSS data alone, pinpointing the exact cause of behavioral changes with the same precision as with photocells would have been more challenging. Further on, during the practical training sessions in the intervention study (Paper 4), the use of photocells to measure speed on the hilltop was necessary to facilitate immediate feedback after each trial.

In the mass-start competition (Paper 3), speed and position were measured using AdMos 10 Hz GNSS device. However, the accuracy of this GNSS device had not been previously assessed in this specific setting. To evaluate the accuracy, the times obtained from the GNSS measurements were compared with the official split times provided by the organizer. The comparison revealed a mean offset of less than 0.01 s with a standard deviation (SD) of 0.30 s across all 17 split times and 42 skiers.

One strength of Paper 4 is that speed profiles from all top 45 skiers were included. To achieve this, a method was developed to synthesize data on position and time along the racecourse for the seven skiers who had missing speed profiles. These seven skiers consisted of three skiers that did not wear sensors due to their low ranking, and four skiers had missing data in the GNSS trace. The model used for synthesis employed a deep learning approach (i.e., machine learning) and utilized the official race timing data (i.e., 17 points along the racecourse) from the 38 skiers with speed profiles of sufficient quality as input data. However, a limitation of the study was that GNSS technology does not possess the necessary level of accuracy to detect relative positions in the field, thus restricting the ability to examine group dynamics.

5.4.2 Physiological measures

Since HR is unobtrusive and easy to measure, and often used as a real-time proxy for $\dot{V}O_2$ during steady state and non-steady-state exercises, a study was conducted indoors in a controlled laboratory setting to simultaneously measure HR and $\dot{V}O_2$ at different intensities and varied terrain. As earlier stated, several similarities between HR and $\dot{V}O_2$ were observed. Both HR and $\dot{V}O_2$ fluctuated in response to the terrain, and the timing of the peak values of HR/$\dot{V}O_2$ (occurring in relation to the uphill) was consistent and independent of intensity. Additionally, both HR and $\dot{V}O_2$ exhibited a delayed response to changing workload, as previously demonstrated (Gløersen et al., 2018b; Gløersen et al., 2020). This delay is likely attributable to a delayed physiological response (Barstow and Molé, 1991) and measurement delays (such as the low resolution of $\dot{V}O_2$ data and signal processing of the instantaneous HR). However, there were also differences. The rate of decrease during downhill sections varied with intensity and was lower for HR compared to $\dot{V}O_2$. Furthermore, unlike $\dot{V}O_2$, HR showed a significant drift over time, known as cardiovascular drift, which was dependent on intensity and duration, with a greater drift observed at higher intensities. Cardiovascular drift is characterized by an increase in HR during prolonged exercise to compensate for a decrease in stroke volume and mean arterial pressure. The magnitude of the drift depends on exercise intensity, duration, subject training status, dehydration/hypohydration, and/or environmental conditions (Lafrenz et al., 2008; Souissi et al., 2021). The exact mechanisms underlying cardiovascular drift are unknown, but one of the main theories suggests that increased skin blood flow leads to blood volume displacement from the central circulation to the periphery, reducing stroke volume. The rise in HR is likely a response to the decrease in stroke volume and mean arterial pressure (Souissi et al., 2021). Due to these differences, the use of %HR to accurately indicate %$\dot{V}O_2$ during interval-like or continuous exercise appears to depend on several factors, including duration, intensity, and intensity fluctuations. This is supported by other studies in cycling (Boulay et al., 1997; Bot and Hollander, 2000; Tucker et al., 2006) and in XC skiing (Staunton et al., 2022a). Specifically, (Staunton et al., 2022a) found that HR overestimated $\dot{V}O_2$ during moderate intensity but underestimated $\dot{V}O_2$ during high-intensity in both roller skiing and cycling. Altogether, those findings have important implications for assessing %HR during training and competitions, and therefore HR measurements must be interpreted with caution. A practical solution may involve complementing HR measurements with subjective assessments of perceived exertion and analyzing blood lactate concentration during selected sessions to guide exercise intensity during training.

Complementary to HR and $\dot{V}O_2$ measurements, oxygen saturation in working muscles, estimated from NIRS measurements (i.e., in our study presented as tissue saturation index (TSI)) may provide indications about the local metabolism in the workings muscles. However, since this technology is based on an optical sensor placed on the skin, it can only measure the local oxygenation in the tissue beneath the sensor. Also, the depth of penetration of the light in the body will depend on many factors, so to what extent this measure can estimate the real oxygen saturation in the muscles is unknown and will vary between individuals and locations on the body. The optical signals are also sensitive to inhomogeneous conditions under the sensor, and motion artifacts. To assess the quality of the data, a fit factor (TSI fit factor) is provided for each TSI sample. This factor derives from an algorithm that compares the absorption in the tissue over three distances, and when the absorption levels are very similar, the TSI fit factor will be close to 100 (%). Even though TSI is an absolute measure, changes, and baseline TSI values can differ between subjects due to differences in body composition, whereas TSI values are stated to be reproducible within a subject. Typical TSI values for measurements on human tissue in healthy conditions are 55-80% during rest, while during exercise, TSI in muscle tissue can drop to 10-20%[2]. Accordingly, it may be difficult to use this parameter to compare subjects, however it may be used to track relative changes according to intensity, terrain, and sub-techniques for one subject if the sensor is kept on the exact same location on the body.

In our studies, the NIRS sensors were placed on the arms (triceps brachii) and legs (vastus lateralis), and a fit factor of 99.8% were used to filter the data. Still, the TSI data was assessed as noisy (probably due to motion artifacts), and the results must be interpreted with caution. Mean values for TSI_{arm} were less than mean values for TSI_{leg} at both low- and high-intensity. This indicates less oxygen saturation in the arms than the legs at both intensities and corresponds with the fact that at

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[2] https://www.artinis.com/blogpost-all/2022/tissue-saturation-index-tsi-absolute-oxygenation-measure-in-local-tissues

both intensities the skiers adapt their technique to the workload by generating more power from poling than ski push offs. We also found that the TSI values for both arms and legs decreased significantly from low-to high-intensity (arms/legs: 3.8/6.3%-points) which indicates that TSI-values could be used as a relative measure of intensity. Also, similarly to HR and $\dot{V}O_2$, the TSI-values fluctuated according to the terrain both at low- and high-intensity, with the same timing of the peak values relating to the steep uphill. However, TSI had a more rapid response to the fluctuating terrain than $\dot{V}O_2$ and HR. Also, to the contrary to HR and $\dot{V}O_2$, the fluctuations were higher during high- than low-intensity. The reason for this is unknow and more research is needed to see if this is due to more motion artifacts during high-intensity, or a real physiological response. Similar fluctuations in muscle oxygen saturation measured by NIRS during interval-like high-intensity training were found when oxygen saturation in working muscles (i.e., biceps brachii, triceps brachii, latissimus dorsi, and vastus lateralis) was measured during successive upper-body sprints (Sandbakk et al., 2015b). Altogether, our studies indicate that NIRS measurements may be able to track variation in tissue-muscle oxygenation according to the terrain and sub-techniques, however there was large individual variability, so it is difficult to use this as an absolute measure to compare subjects. Also, in our study which was performed indoors on roller skis the raw data had a lot of motion artifacts that made the TSI noisy. Studies focusing more specifically on this issue are needed to conclude.

Lactate measurement is often used in both sports and medicine. In response to progressive, incremental exercise, blood lactate concentration (BLa) increases gradually at first and then more rapidly as the exercise becomes more intense. The work rate beyond which BLa increases exponentially (known as the lactate threshold) has been found to be a better predictor of performance than $\dot{V}O_{2max}$ and in addition a better indicator of exercise intensity than HR (Goodwin et al., 2007). Therefore, BLa in relation to the lactate threshold is commonly used to steer the intensity. However, the lactate threshold may vary between individuals from as low as 1.4 mmol/L to as high as 7.5 mmol/L (Stegmann et al., 1981), so this parameter should be individualized like HR or interpreted with caution. Today research and development are ongoing to enable wearable, continuous lactate monitoring system, however this is challenging task and currently the accuracy of those systems is not good enough (Van Hoovels et al., 2021; Chien et al., 2022; Tehrani et al., 2022). Therefore, BLa can only be measured as point measurements, and during XC skiing the skier must stand still and take of the glove/pole during the measurements. In Paper 2, Bla after warm-up/low-intensity protocol (values between 1.0-2.3 mmol/L) was found to have a high correlation (R = 0.82) with final ranking in the simulated mass-start. Also, a medium correlation (R = 0.58) was found between BLa (values between 7.2-18.7 mmol/L) measured after the all-out-sprint and final ranking. For XC skiers it can be valuable to measure BLa during reference sessions where the external load is known to measure progression, or to control that the threshold interval sessions are not too hard. In addition, BLa can be used to measure the state of the body after a controlled warm up (with known external load) before important, high-intensity sessions.

5.4.3 Biomechanical parameters

Biomechanical analysis in XC skiing relies on accurate sub-technique detection and classification. At the beginning of this thesis, models for sub-technique classification in the skate style were not available. Therefore, the thesis commenced with data collection and the development, training, and testing of a model aimed at identifying different cycles and classifying them into the various sub-techniques in skate style (section 3.5). The trained support vector machine learning model could accurately identify different cycles and classify them into sub-techniques with over 99% accuracy in the indoor studies (Paper 1 and Paper 2). When applied to outdoor conditions, the model demonstrated an overall classification accuracy of 91-95%. The model employed 96 different normalized features based on 3D accelerometer data from a single IMU located on the chest, similar to a method used in the classical style (Rindal et al., 2017). However, in the classical style model, data from two different IMUs were required, with the sensor on the arm used for cycle identification and the sensor on the chest used for classification. In contrast, our skate style model only required data from a single IMU. The cycle detection in our model was based on sideways movements of the upper body, with the start of the cycle defined as the point at which the upper body was in a "left position" with the lowest acceleration. To ensure the applicability of this method to skiers with different skill levels and in various settings, the model was trained using data from a range of skiers, including recreational and world-class skiers, during both indoor roller skiing on a treadmill and outdoor skiing on snow. The G5 sub-technique showed lower sensitivity and precision compared to G2, G3, and G4. This is likely due to the G5 sub-technique being similar to the different turn techniques employed outdoors. Naturally, during outdoor conditions, due to the inhomogeneity and turns in the course, as well as more use of the G5 sub-technique, the model exhibited lower accuracy compared to indoor treadmill settings.

To measure if the skiers changed their behavior and improved acceleration on the hilltop after the intervention, a measure for the biomechanical work intensity on the hilltop, called total variance of chest acceleration (*totVarAcc*), was derived (Paper 4). This measure was derived from a single accelerometer sensor that captured the intensity of both active poling and leg kick (see appendix 8). The results from the IMU located on the chest were presented in this study, but similar results were found for the IMU located on the upper back. The metric was based on calculating the signal power of time-discrete signals, which can be divided into a dynamic part and a static part. Since only the skiers acceleration/intensity on the hilltop was relevant in our study, only the dynamic part of the signal power was included. To eliminate the influence of external conditions, the change in this parameter from Day 1 to Day 2 for the intervention group was compared with the same measure for the control group. Similar metrics, such as *PlayerLoad*^{TM} (Montgomery et al., 2010; Casamichana et al., 2013) and the more recent metric average net force (*AvFnet*) (Staunton et al., 2022c) have been used to monitor load by interpreting accelerometer data in various sports, especially when the sensor is placed close to the center-of-mass (Staunton et al., 2022c). In our study, our metric, *totVarAcc* and a filtered version of *AvFnet* (filtered) showed similar outcomes for most segments, while *PlayerLoad*^{TM} did not yield a significant difference between the intervention group and the control group for 4 out of 5 segments (**Table 8**). *PlayerLoad*^{TM} is the sum of the accelerations across all axes of the 3D accelerometer during movement divided by a scaling factor[3]. It has been used for athlete monitoring in team sports such as soccer (Casamichana et al., 2013) and basketball (Montgomery et al., 2010) to quantify biomechanical stress, but it has also been shown to correlate with physiological measures such as HR, $\dot{V}O_2$ and RPE (Montgomery et al., 2010; Casamichana et al., 2013). However, significant variations exist between subjects in the magnitude of *PlayerLoadTM*, and caution should be exercised when making comparisons between athletes and when using recordings to identify lower-limb movement patterns (Barrett et al., 2014). Therefore, this metric may not be suitable for XC skiing. *AvFnet* is the product of the filtered instantaneous resultant acceleration vector and participants body mass averaged over the selected period. It has been shown to predict exercise intensity in basketball and to be correlated with $\dot{V}O_2$ and running speed (Staunton et al., 2022c). In Paper 4, for this metric to be meaningful, the acceleration signals in each direction need to be appropriately high pass filtered, with a cutoff frequency smaller than the longest cycle. However, in our study, *totVarAcc* was chosen, due to its fundamental analogy to signal power computation, and its relative ease of implementation.

Being able to precisely measure micro-parameters (i.e., inner-cycle parameters) in XC skiing is necessary to be able to understand differences between skiers at different levels in execution of sub-techniques as a function of intensity and terrain. Micro-parameter data can also be used to measure effects of fatigue or provide an objective tool for improving technical aspects of XC skiing and effects of different equipment (i.e., skis, poles, bindings, boots). Previously, one limited study has used IMU data placed on the ski boots and poles to measure contact time for poles and skis in skate during indoors conditions (Myklebust et al., 2014), while in most skate studies, these parameters have mainly been obtained using a marker-based, multiple cameras system or force sensors

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[3] https://support.catapultsports.com/hc/en-us/articles/360000510795-What-is-Player-Load-

(Sandbakk et al., 2012a; Sandbakk et al., 2015a). In Paper 1, contact times for skis and poles in the main sub-techniques (i.e., G2, G3 and G4) for low- and high-intensity skiing in the fluctuation terrain were presented. The method was developed using simultaneous measurement with two different systems; 1) IMU sensors placed on arms and skis and 2) marker-based, multiple cameras system (Meyer et al., 2022c). In addition to the contact time, swing time was measured. The overall precision for these parameters ranged from 19 to 66 ms, corresponding to 3.0% to 7.8% of the corresponding duration. Also, this method was used to describe differences and similarities between G2 and G4-sub-techniques while roller ski-skating on a treadmill (Meyer et al., 2021). Further on, a study aiming to adapt the treadmill-developed method for determination of micro-parameters in XC roller ski skating for field applications was performed (Meyer et al., 2022a). Here the precision ranged from 49 to 59 ms for the micro-parameters, corresponding to 3.9% to 13.7% of the corresponding durations.

5.4.4 Change of behavior

Usually, in sport and health research and applications, sensors are used to measure physiological or biomechanical parameters to gain knowledge of performance, technique or about the human body (Marsland et al., 2015; Seeberg et al., 2017; Karlsson et al., 2018; Solli et al., 2018; Berg-Hansen et al., 2022). Recently an intervention study investigated whether skiers with a fast-start pacing pattern could increase time-trial performance by use of a more even pacing strategy using data from GNSS sensors (Losnegard et al., 2022). The skiers with a pronounced high start speed were instructed to start with a lower speed, and improved performance in the second race compared to a control group. In this thesis we took the use of sensors a step forward and explored how objective sensor data could be used actively during training to change behavior (Paper 4). We found that the methodology with targeted training combined with video- and sensor-based feedback led to successful implementation of the terrain-specific micro-pacing strategy in XC skiing, which induced higher speed and reduced time in a specific targeted downhill segment as well as overall downhill- and flat terrain, compared to a control group. The combination of the theoretical lecture, including both video and speed analysis, highlighting the potential to gain seconds, and the objective sensor-feedback directly after each trial during the training session, likely were vital points to create an effective learning process for the skiers. Since the time used for this intervention-training was less than two hours, an interesting question is also whether a longer intervention period, including several training sessions with feedback in different racecourses could improve skiers micro-pacing strategy even more.

The methodology used can also be generalized and transferred to other cases. For example, in the AutoActive project we have used similar methodology on persons with multiple sclerosis (pwMS). Here we first performed a study where we characterized walking pattern using IMUs for 46 pwMS and found that particularly one parameter, the angle in the ankle during the push-off phase, correlated with performance (Berg-Hansen et al., 2022). Specifically, we found that a large angle on the ankle was important for a fast walking speed and were able to set a critical minimal limit for this parameter (Berg-Hansen et al., 2022). Thereafter, the physical therapist could use this knowledge on other pwMS by measuring walking pattern with the IMUS, and if they are below the critical limit, he could instruct them on how to improve their walking speed with video and the measure of this angle. After a rehabilitation period, we could measure the effect of this training (Simonsen, 2022). Accordingly, this methodology may provide an effective learning process to improve technical or tactical skills in different sports or during rehabilitation. However, it is important to have full control of what the sensor can measure (and not measure) and use this objective feedback in the learning process.

5.5 Integrative understanding

5.5.1 Combination of sensor data from different sources.

Without context and correct interpretation, raw sensor data can be an incomprehensible stream of data. Therefore, it is often necessary to combine data from different sensors and develop algorithms and models to get an integrative understanding and provide new knowledge. When assessing performance in outdoor XC skiing different types of sensor data are needed. Firstly, one needs to measure the movement and automatically recognize the different cycles and sub-techniques. In addition, it is important to measure the physiological responses, and the position in the terrain. Finally, you need to synchronize the sensor data to a common timeline and present them in relation to the terrain for exploration. In XC skiing, this type of data was for the first time collected and presented by Seeberg et al. in 2017 (Seeberg et al., 2017). This study was performed in classical style, and a model was developed to detect sub-techniques from multiple IMUs and for the first time combined with HR and GNSS data which enabled the relation of sub-technique, cycle length/cycle rate, intensity, speed and position to the terrain, and thereby gain knowledge in outdoors XC skiing (Seeberg et al., 2017). Here many of the sensors were integrated in a common system that provided synchronized data. However, often the needed sensor data are from different sources and therefore need to be synchronized in time with high accuracy before the data can be explored and give an integrated understanding. Without a clear methodology and adequate tools, this task can be surprisingly difficult since it is hard to identify characteristics points in the data streams without a context. In addition, the crystal oscillator, i.e., the internal “clock” in each sensor system, has a limited accuracy and differs from system to system. Accordingly, it is highly important to decide how to synchronize the different data in front of the data collection and include the required steps in the protocol. A major delivery in the AutoActive project was a tool to facilitate sensor-based research on human activity. The open-source software, AutoActive Research Environment, was developed to simplify the process of visualizing, synchronizing, and organizing data, such as sensor data and videos from multiple sources (Albrektsen, 2021). The strengths of this tool were the ability to synchronize video with sensor data from multiple sources, and visualizing videos and sensor data side by side combined with algorithms developed in Matlab or Python. In this thesis it was used for synchronizing sensor data with video, labeling data and for visualizing of the derived models for sub-technique classification (developed in Matlab) together with the video. In addition, it was used to visually compare biomechanical parameters of different skiers together with video while exploring the data in the indoor studies.

5.5.2 Research methodology for an integrative understanding

To enable an integrative understanding in sport and health applications, different steps are needed. First, the research question needs to be defined - what kind of knowledge is desired and what level of precision is required, as well as how the data will be used. Secondly, one must understand the relationship between different measurements and the effect of different situations. Thirdly, one must choose different technologies that can measure this, and present the data in a way so that they can be used effectively.

In this thesis we wanted to enable assessment of physiological and biomechanical responses in XC skiing in relation to the fluctuating terrain using sensor data. Three specific research questions were defined; 1) Why XC skiers that compete at high-intensity are training most of the time at low-intensity? 2) What are the performance-determining factors for XC skiing mass-starts? 3) How can sensors data be used to change behavior and improve micro-pacing in XC skiing? Further on, the multidisciplinary team in AutoActive consisting of experienced researchers with competence in sensors, data science, biomedical research, physiology, sport science and domain competence in elite XC skiing enabled understanding of the accuracy and the relationship between different measurements (physiological, biomechanical and performance data) in outdoor field measurements and indoor, more standardized conditions (roller skiing on a treadmill). Finally, we chose the appropriate methods and technologies needed to answer the different research questions, based on the parameters needed and required accuracy.

To answer the first research question, we complemented outdoor methodology with standard measurements available in the laboratory under standardized conditions. We used accurate reference sensors and methodology aiming to build competence on how to interpret data from sensors employed outdoors. The advantage of this protocol was that both physiological and biomechanical variables could be measured more accurately and with stable, controlled conditions than outdoors on snow. However, the same set speed and incline was used for all skiers and the differences between our setup and real-life situations when skiing outdoors require interpreting our results with caution. Accordingly, the design of Paper 1 allowed us to investigate the underlying physiological and biomechanical mechanisms while skiing at low- and high-intensity and thereby increasing the generalizability of our results. A tradeoff, however, was a limitation in ecological validity and that other settings for speed or incline (i.e., if the skiers could choose speed freely) could have changed the result. Even so, our protocol reflects the reality of elite skiers, who often perform low- and high-intensity training together in groups.

For the second research question, the determinants for mass-start, a combination of an indoor and an outdoor study were performed. The indoor study was a simulated mass-start performed roller skating on the treadmill with the same sensor setup as in Paper 1. This allowed us to study the underlying physiological and biomechanical mechanisms and generalize on the impact of these variables on performance. A limitation is, however, to enable direct comparison between the different skiers, speed was preset for each incline. The incline–speed combinations were carefully selected, so that the best skiers were able to complete the protocol and increase intensity during the final sprint, and on the other hand some of the skiers needed breaks in order to complete the protocol. Still, the results could have differed if the speed or inclines were set to different values. The outdoor study explored an official FIS-regulated mass-start competition with over 140 participants, including many national- to world-class skiers. As many as 57 skiers were equipped with high-end GNSS sensors and we were able to measure speed profiles for most of them. Even though the snow conditions made the racecourse short and narrow, the temperature, snow conditions and tracks were relatively stable during the competition, with even conditions for all skiers. Another strength of the study was the combination of objective speed profiles with the subjective information assessed from the questionnaire. A limitation of the outdoor study was that physiological responses and biomechanical analyses were not included. Interesting things to study would have been the physiological response to the different pacing-patterns, sub-technique selection and cycle rate during different part of the race, and particular in the final sprint.

Lastly, for the third research question an intervention study was performed outdoors with two simulated time trials on snow as end points, with an intervention in between. Here, we recruited 28 skiers that completed two time-trials with individual start every second minute. That enabled the attachment of multiple wearable sensors providing measurement of HR, IMU-data and GNSS traces. In addition, timing of short segment and speed was measured by photocells during the race and for immediate feedback during the practical training session.

To summarize, with carefully designed protocols sensor data can be used to measure performance, physiological responses, and movement techniques during outdoor conditions to get an integrative understanding of XC skiing. Additionally, we also showed that it can be beneficial to complement outdoor studies with simulated indoor studies in controlled conditions to provide new knowledge.

A general limitation in this thesis is that only males were included. The main reason for this was that it was not possible to recruit enough females with adequate performance level. In Paper 3, the mass-start competition there were a mass-start with females later the same day, however we only had equipment to measure on one race. Since there were 143 starters in the male and only 68 in the female race, the male race was prioritized to enable a more equal skills-level of the participants and thereby a higher ecological value. In Paper 4, the two females that were available for the study completed the protocol but were not officially included in the study due to a too small cohort.

6 Conclusion

The main objective of this thesis was to investigate physiological responses, movement techniques and their associations with training intensity and performance in cross-country skiing using sensor data, with a particular emphasis on mass-start competitions and the skating technique.

In Paper 1, the study explored the specific physiological and biomechanical stimulus provided during low-intensity training and its similarities to the demands of competitions, conducted indoors in controlled environments. The findings revealed several similarities between low- and high-intensity training, especially in less strenuous terrain, suggesting that important demands for cross-country skiing competitions can be adequately stimulated during low-intensity training. This helps explain the benefits of low-intensity training, as it allows for a high training volume while minimizing accumulated fatigue.

This thesis provides the first scientific descriptions of race development and performance determining factors in a mass-start cross-country skiing competition. In Paper 2, it was found that mass-start competitions share similarities with individual time trials, such that higher endurance capacity and skiing efficiency were associated with better mass-performance. Furthermore, uphill was found to be the most performance differencing terrain and the best skiers used more demanding skiing sub-techniques and associated macro parameters in steep terrain than the lower performing skiers. However, a novelty was that the endurance capacity and skiing efficiency seem to play a different role in mass-starts than shown for time-trials. Instead of using a superior endurance capacity and skiing efficiency to ski faster than lower-level peers throughout the entire race, which is normally the case during time-trials, our findings imply that skiers who score high on these performance determining variables can save energy and are therefore able to utilize their "reserves" better at the end of the race and in the final sprint. In Paper 3, which examined a real mass-start competition, it was found that the skiers moved in dynamic packs to benefit from drafting, with most skiers employing the strategy of following the leader as long as possible. This led to a more positive pacing pattern (i.e., higher intensity in the first part of the race than the last part) for the lower-performing skiers that may have been sub-optimal for their physiological performance. In sum, the key factors determining mass-start performance were found to be adequate starting position, ability to avoid incidents and disadvantages from the accordion effect, tolerance for intensity fluctuations, maintaining speed throughout the competition (especially in uphill terrain), and possessing well-developed final sprint abilities.

In Paper 4, the use of sensors was taken a step further to explore how objective sensor data could provide feedback and induce behavioral changes. The study demonstrated that targeted training, combined with video- and sensor-based feedback, successfully implemented a terrain-specific micro-pacing strategy in cross-country skiing. This strategy resulted in higher speed and reduced time spent in downhill and flat terrain sections compared to a control group.

Overall, the studies presented in this thesis offer novel insights into the physiological and biomechanical factors that underpin cross-country skiing performance, including the importance of pacing strategy, group dynamics, technique, and other performance-determining factors in mass-start competitions. The combined use of various sensors, adapted signal processing, and smart classification and detection models holds the potential to provide valuable insights into the interconnected physiological and biomechanical demands of cross-country skiing. Moreover, these tools can be directly applied in training to enhance the quality of each session and effectively improve technical and tactical skills.

7 References

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8 Appendix - Moving variance and the total variance acceleration metric

The *totVarAcc* metric used in the thesis was motivated by the power signal and its relation to statistical power. The power signal (*Px*) can be divided into two parts, the dynamic and the static part.

$$Px = \frac{1}{\mathrm{N}}\sum_{i=1}^{N-1}|X(i)|^2 = \frac{1}{\mathrm{N}}E\{|X(i)|^2\} = \frac{1}{\mathrm{N}}(E\{X(i)-\mu\} + E\{X(i)\}^2) = \frac{1}{\mathrm{N}}(\sigma^2 + \mu^2\ )$$

Since we were interested in the skiers intensity and link that to the "amount of movement " within the sub-technique cycles we only considered the dynamic part of the power, the variance.

The basis for the *totVarAcc* metric is given below: Let $a \in x, y, z$ be a sequence of acceleration samples of length N. And W denote the decried odd numbered moving window $1 < W < N$. Then the algorithm moving window w_j, where $j > 1$, will handle the W truncation around the beginning and end of the signal a, and is defined by:

$$w_j = min(W, 2(j-1)+1, 2(N-j)+1)$$

Let the sample average be given by:

$$\mu(a,j) = \frac{1}{w_j}\sum_{i=j-(w_j-1)/2}^{j+(w_j-1)/2} a\,(i)$$

And the sample variance by:

$$var(a,j) = \frac{1}{w_j - 1}\sum_{i=j-(w_j-1)/2}^{j+(w_j-1)/2} |a(i) - \mu(a,j)|^2$$

$$var(a,1) = \sum_{i=1}^{2}\left|a(i) - \frac{a(1)+a(2)}{2}\right|^2$$

$$var(a,N) = \sum_{i=N-1}^{N}\left|a(i) - \frac{a(N-1)+a(N)}{2}\right|^2$$

Then the $totVarAcc$ metric can be formulated as:

$$totVarAcc = \sum_{a\in(x,y,z)}\left\{\frac{1}{N}\sum_{i=1}^{N} v\,ar(a,i)\right\}$$

Furthermore by compiling an array, $movvar(a,W)$, of the variances,

$$movvar(a, W) = [var(a, 1), var(a, 2), \dots, var(a, N)]$$

the $totVarAcc$ metric can be written:

$$totVarAcc = \sum_{a \in (x,y,z)} \left\{ \frac{1}{N} \sum_{i=1}^{N} m\, ovvar(a, W)_i \right\}$$

where i denotes the i'th element of the array $movvar(a, W)$. Matlab provides the $movvarfunction$ to generate the above precented array.

9 Original publications

Paper 1

frontiers
in Physiology

ORIGINAL RESEARCH
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Physiological and Biomechanical Responses to Cross-Country Skiing in Varying Terrain: Low- vs. High-Intensity

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The purposes of our study were to investigate the physiological and biomechanical responses to low-intensity (LI) and high-intensity (HI) roller ski skating on varying terrain and compare these responses between training intensities. Nine elite male skiers performed treadmill roller skiing consisting of two 21 min sessions (7 × 3 min laps) at LI and HI with the same set inclines and intensity-dependent speeds (LI/HI: distance: 5.8/7.5 km, average speed: 16.7/21.3 km/h). Physiological and biomechanical variables were measured continuously, and each movement cycle and sub-technique employed were detected and classified with a machine learning model. Both the LI and HI sessions induced large terrain-dependent fluctuations (relative to the maximal levels) in heart rate (HR, 17.7 vs. 12.2%-points), oxygen uptake ($\dot{V}O_2$, 33.0 vs. 31.7%-points), and muscle oxygen saturation in the triceps brachii (23.9 vs. 33.4%-points) and vastus lateralis (12.6 vs. 24.3%-points). A sub-technique dependency in relative power contribution from poles and skis exhibited a time-dependent shift from Lap 1 to Lap 7 toward gradually more ski power (6.6 vs. 7.8%-points, both $p < 0.01$). The terrain-dependent fluctuations did not differ between LI and HI for $\dot{V}O_2$ ($p = 0.50$), whereas HR fluctuated less ($p < 0.01$) and displayed a time-dependent increase from Lap 2 to Lap 7 (7.8%-points, $p > 0.01$) during HI. Oxygen saturation shifted 2.4% points more for legs than arms from LI to HI ($p > 0.05$) and regarding sub-technique, 14.7% points more G3 on behalf of G2 was employed on the steepest uphill during HI ($p < 0.05$). Within all sub-techniques, cycle length increased two to three times more than cycle rate from LI to HI in the same terrains, while the corresponding poling time decreased more than ski contact time (all $p > 0.05$). In sum, both LI and HI cross-country (XC) skiing on varying terrain induce large terrain-dependent physiological and biomechanical fluctuations, similar to the patterns found during XC skiing competitions. The primary differences between training intensities were the time-dependent increase in HR, reduced relative oxygen saturation in the legs compared to the arms, and greater use of G3 on steep uphill terrain during HI training, whereas sub-technique selection, cycle rate, and pole vs. ski power distribution were similar across intensities on flat and moderately uphill terrain.

Keywords: near-infrared spectroscopy, XC skiing, low-intensity training, inertial measurement unit, sub-technique detection, power, high-intensity training

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INTRODUCTION

Cross-country skiing is a demanding endurance sport that involves continuous changes in speed, external power, and energy system contributions while skiing across varying terrain. Added to the high aerobic metabolic power required to excel in cross-country (XC) skiing, sufficient anaerobic power and well-developed efficiency with associated technical and tactical skills are of high importance (Sandbakk and Holmberg, 2017). XC skiing is further complicated by continuous shifts between sub-techniques and the adaption of cycle rate (CR) and cycle length (CL) according to the topography of the track, during both training and competitions (Holmberg, 2015; Sandbakk and Holmberg, 2017).

For those reasons, training for XC skiers aims to improve their performance at high, competitive intensities, and even if the mean intensity is aerobic (i.e., 90–95% of $\dot{V}O_{2max}$), relatively substantial anaerobic contributions are shown to support aerobic energy delivery. There are large variations in the exercise intensity during races according to the change between uphill, flat, and downhill terrains. Several studies have shown work rates requiring ∼110–160% of the maximal oxygen uptake ($\dot{V}O_{2max}$) of a skier on relatively short uphill segments during competitions (Gløersen et al., 2018; Karlsson et al., 2018; Losnegard, 2019), thereby combining nearly maximum aerobic energy delivery with significant amounts of anaerobic metabolic support. While such repeated bursts of high uphill work rates cause the substantial accumulation of fatigue, the strategy is possible due to the natural recovery allowed during subsequent downhill were external power requirements are nearly zero while flat segments also have smaller power requirements than in uphill (Losnegard, 2019).

Even though XC skiing competitions are performed at a high intensity (HI), with HI sessions regarded as a key stimulus in the development of XC skiers, most of the training is performed as long-duration sessions of skiing or roller skiing at low intensity (LI) (Sandbakk and Holmberg, 2017). LI training is regarded beneficial as it allows a large volume of training by keeping the degree of accumulated fatigue low (Sandbakk and Holmberg, 2017). However, LI sessions performed as XC skiing in varying terrain have been shown to induce significant terrain-dependent fluctuations in power output and heart rate (HR) (Bolger et al., 2015; Solli et al., 2018; Haugnes et al., 2019). As a result, the choice of sub-technique, kinematic patterns, and the loading of arms and legs will be challenged to various degrees depending on the terrain and intensity. Compared with most other endurance sports, those demands of XC ski-specific training and competitions are unique. Thus, this interval-based physiological and biomechanical stimulus in XC skiing, including the differences between LI and HI training, requires a more detailed elucidation.

In outdoor XC skiing, environmental conditions such as snow quality, air, and snow temperature, tracks, and wind influence skiing speed, choice of sub-technique, and cycle length, cycle rate, and the power distribution from arms and legs. This will, in turn, affect the metabolic demands. The combined use of various wearable sensors with adapted signal processing and smart classification and detection models stands to afford new, important insights into these interrelated physiological and biomechanical demands of XC skiing. For example, data from inertial measurement units (IMU) can be used to automatically detect XC sub-techniques and related macro and micro-kinematic patterns of skiers in the field without using resource-intensive methods such as video analysis (Seeberg et al., 2017, 2021; Rindal et al., 2018; Tjønnås et al., 2019). However, the few studies that have involved collecting such data to investigate LI vs. HI skiing were performed outdoors and limited by a lack of control over external conditions. To extend such work, a comprehensive understanding of the physiological and biomechanical demands of XC skiing under standardized conditions is necessary to subsequently take full advantage of those new possibilities in the field (Bolger et al., 2015; Solli et al., 2018; Haugnes et al., 2019). As an initial step, we, therefore, sought to complement an outdoor methodology with standard measurements available in the laboratory under standardized conditions using highly accurate reference sensors and methodology aiming to build competence on how to interpret data from sensors employed outdoors. Accordingly, the purposes of our study were to investigate physiological and biomechanical responses to LI and HI roller ski skating on varying terrain and to compare the responses between training intensities.

METHODS

Overall Design

We measured physiological and biomechanical variables among elite skiers performing the same course at both LI and HI while roller ski skating on a treadmill. The data used represented a subset of a larger dataset of which parts have been presented in other studies with different aims and contexts (Noordhof et al., 2021; Seeberg et al., 2021). The protocol consisted of two consecutive parts performed on the same day with a 5 min recovery period in-between, each with the same preset load for all skiers: a 21 min LI bout to simulate a LI training session and a 21 min HI bout to simulate a mass-start or a HI training session. Initially, 13 elite male Norwegian skiers, consisting of eight XC skiers [distance International Ski Federation (FIS) points: 47 ± 21] and five biathletes, were recruited for the study and performed the protocol. The skiers who could not meet the required workload of the HI session were given one or more 30 s breaks (i.e., by grabbing a rope at the front of the treadmill, thereby simulating tuck) before they continued skiing the set protocol and only the nine skiers who completed the protocol without breaks were included in our study. $\dot{V}O_2$, HR, near-infrared spectrometry (NIRS), kinematics, and pole forces were monitored continuously, whereas blood lactate concentration (BLa) and rating of perceived exertion (RPE) were measured directly after each session.

Participants

Anthropometric, physiological, and performance characteristics of the nine elite, male skiers included in the study are given in **Table 1**. All skiers, healthy and free of injury at the time of testing, were instructed to prepare in the same manner as before

TABLE 1 | Anthropometric, physiological, and performance characteristics (*M* ± *SD*) of the nine male skiers in the study.

Variables	*M*	*SD*
Age [years]	25.9	2.2
Body height [cm]	185.7	6.7
Body mass [kg]	80.1	5.5
Body mass index [kg · m^{-2}]	23.2	1.0
VO_{2max} [mL · min^{-1} · kg^{-1}]	70.6	3.3
VO_{2max} [mL · min^{-1}]	5,653	282
HR_{max} [beat · min^{-1}]	191.7	7.3
Skinfold thickness of triceps brachii (arm) [mm]	6.1	1.6
Skinfold thickness of vastus lateralis (leg) [mm]	7.5	1.5

HR_{max}: The highest measured heart rate (beat·minute^{-1}) during the protocol. $\dot{V}O_{2max}$: The highest 30-s moving average (based on 10-s mixing chamber values) during the incremental maximum test in the pretest.

a competition, without performing strenuous exercise during the last 24 h before the test. The skiers were conversant with treadmill roller skiing and $\dot{V}O_2$ measurements from previous testing sessions and daily training routines.

Equipment

The protocol was performed on a 3-by-5-m motor-driven treadmill (ForceLink S-Mill, Motekforce Link, Amsterdam, the Netherlands) on roller skis with a friction coefficient of 0.016 [(see Seeberg et al. 2021) for details on the ski equipment and friction measurements].

Before testing, the body mass of each skier was determined on an electronic scale (Model No. 877, Seca GmbH and Co. Hamburg, Germany). Respiratory variables were measured continuously using open-circuit indirect calorimetry (Oxycon Pro, Erich Jaeger GmbH, Hochberg, Germany) and details of the setup and the calibration procedures are referred to in Seeberg et al. (2021). The data were collected as 10 s mixing chamber values and are presented as relative to body weight and as a percentage of $\dot{V}O_{2max}$ (%$\dot{V}O_{2max}$).

A Forerunner 920XT sports watch (Garmin Ltd., Olathe, KS, USA) was used to continuously measure HR at a sampling frequency of 1 Hz. Relative HR (%HR_{max}) was calculated as the percentage of maximal HR (HR_{max}) for each skier, and HR_{max} was the highest measured value for each person, which was obtained either in the HI session or in the protocol for determining $\dot{V}O_{2max}$ (protocol described in chapter 2.4). BLa was measured using a Biosen C-line Sport Lactate Measurement System (EKF Industrial Electronics, Magdeburg, Germany) after collecting 20 μl of blood from the fingertip. The device was calibrated every 60 min with a 12-mmol μl standard concentration. Rating of perceived exertion (RPE) for the upper body, lower body, and overall was recorded using the 6–20-point Borg Ratine of Perceived Exertion (RPE) Scale (Borg, 1982).

Muscle oxygenation was assessed using a wireless NIRS system (Portamon, Artinis Medical Systems, Elst, the Netherlands) consisting of two optodes [see details in Seeberg et al. (2021)]. Data from the two optodes was collected and synchronized in time by the designated software, and the tissue saturation index (TSI) with a fit factor exceeding 99.8% was used. Herein, TSI_{leg} indicates the TSI from the sensor placed on the vastus lateralis in the right leg, whereas TSI_{arm} is the TSI from the sensor placed on the long head of the triceps brachii in the right arm.

Eight Oqus 400 infrared cameras captured the 3D position of passive reflective markers placed bilaterally on the body, on roller skis, and on poles, all with a sampling frequency of 200 Hz using the Qualisys Pro Reflex system and Qualisys Track Manager software [Qualisys AB, Gothenburg, Sweden; details given in Seeberg et al. (2021)]. The motion capture system measured only every second lap (i.e., Laps 1, 3, 5, and 7) during LI and HI (the simulated mass start) to reduce the risk of data overload and system failure.

Instrumented ski pole grips (Proskida, Whitehorse, YT, Canada) were used to measure the axial (i.e., resultant) force directed along the poles. The data were streamed to a smartphone *via* Bluetooth and later downloaded to a computer and synchronized with the movement data. The sampling frequency of the force data was 100 Hz.

An IMU placed on the front of the chest (Physiolog 5, GaitUp SA, Lausanne, Switzerland) was used to provide continuous data of the motion of the upper body. The IMU consisted of a 3D accelerometer and 3D gyroscope with a sampling frequency of 256 Hz, in addition to a barometric pressure sensor with a sampling frequency of 64 Hz. The data were stored locally on the sensor and later downloaded to a computer. The movement of the skiers was also visually captured from behind with a video camera (GoPro Hero6, GoPro, Inc., San Mateo, CA, USA) also used to obtain the ground truth.

Protocol for Determining $\dot{V}O_{2max}$

The $\dot{V}O_{2max}$ measurements were taken a separate day before the primary data collection. The protocol of this day can be found in Noordhof et al. (2021). Briefly, the starting incline and speed were 10.5% and 11 km·h^{-1}, respectively, after which the speed was kept constant, while the incline was subsequently increased by 1.5% every minute until 14.0%. Thereafter, the speed was increased by 1 km·h^{-1} every minute until exhaustion. The highest 30 s moving average, based on 10 s mixing chamber values, was defined as $\dot{V}O_{2max}$.

Protocol

After attaching the wearable sensors to the body, the skiers stood still on the treadmill for 4 min while their baseline respiratory measurements were obtained. The active protocol began with a brief calibration procedure (including three jumps used to synchronize sensors from different sources and video) for the IMU sensor before the 18 min warm-up was performed at low to moderate intensity (5 min of G3 at 10 km·h^{-1} with a 5% incline) before two 4 min stages using G2 and G4 (10 km·h^{-1} at an 8% incline).

The 21 min LI session followed the preset terrain profile shown in **Figure 1**. Thereafter, a 5 min recovery period was given before the 21 min HI session was performed on the same inclines but at higher speeds. The HI session was immediately followed by an incremental all-out sprint of which the data were not used

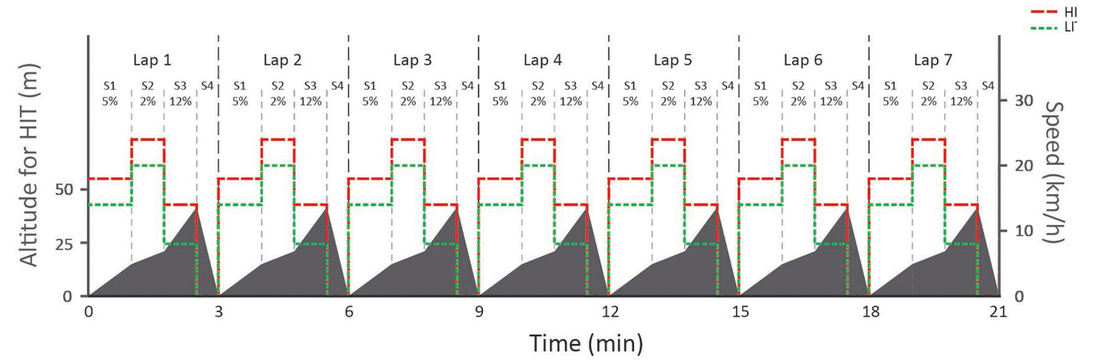

FIGURE 1 | Protocol showing the speed of the treadmill for both the 21 min low-intensity (LI) and high-intensity HI sessions and changes in simulated altitude for the HI session. The course was divided into seven 3 min laps, each containing four segments (i.e., S1–S4) with the same inclines but different speeds for LI and HI.

in this study. The speeds in each segment during LI and HI were carefully selected based on pilot testing and the performance level of the participants. During the entire protocol, each skier received continuous visual and verbal feedback concerning the upcoming terrain and the time until the start of the next segment.

The track in the 21 min LI and HI sessions were organized into seven identical 3 min laps consisting of four different segments simulating a moderately uphill ascent (5%) (i.e., Segment 1), a flat segment (2%) (i.e., Segment 2), a steep uphill ascent (12%) (i.e., Segment 3), and a simulated downhill descent (i.e., Segment 4). The profile of the track was designed according to standards of the International Ski Federation (The International Ski Competition Rules ICR, 2020), in which the following sub-techniques are most commonly used (Andersson et al., 2010): Gear 2 (G2), a technique for skiing uphill (e.g., Segment 3) that involves a double-pole push in connection with every other leg push; Gear 3 (G3), a technique used on moderate inclines (e.g., Segment 1) and level terrain that involves a symmetrical pole push together with every leg push; Gear 4 (G4), a symmetrical double pole push in connection with every other leg push used on level terrain (e.g., Segment 2); Gear 5 (G5) only leg strokes are performed without poling; and Gear 7 (G7), used in a technique applied on downhill terrain (e.g., Segment 4) in which the skier is in a tucked position. In the simulated downhill, the skiers were holding a rope that was attached to the front of the treadmill while they were using a tuck position, thereby simulating G7. Although the track was designed for the use of specific sub-techniques on each segment, the skiers could freely select which sub-techniques they used.

Data Analysis

Cycle Detection and Classification of Sub-techniques

The accelerometer data from the IMU placed on the chest were used to automatically detect and classify each individual cycle into a sub-technique using Gaussian filtering and a trained support vector machine learning model, following a method similar to what Rindal et al. (2018) used. Subsequently, the data were manually examined and corrected for errors in classification by comparing the classified cycles with the video and the graphical representation of filtered accelerometer signals. The accuracy of the model within those data exceeded 99%. Cycle detection was based on the sideways movements of the upper body, with the start of the cycle defined as the point at which the upper body was in a “left-position” with the lowest acceleration. Cycle detection and treadmill speed were used to derive the cycle length (CL) and cycle rate (CR) of each cycle. The cycles were classified into the sub-techniques G2, G3, G4, or other, the last of which included G5, transitions between sub-techniques, simulated downhill skiing (i.e., G7), and non-skiing activities. The algorithms for cycle detection, model development, and the classification of sub-techniques were implemented in MATLAB R2018b (MathWorks, Natick, MA, USA).

Determination of Pole and Ski Contact Time

Accelerometer and gyroscope data from the left and right wrists were used to calculate the contact time for poles (CT_{pole}) by determining the time between initial and terminal pole contact with the ground. Initial contact was set as the first acceleration peak at the beginning of the vibration phase induced by the touching of the ground by the pole, while terminal contact was obtained as the highest acceleration peak close to the minimum angular speed induced by the change in direction of the motion to bring the poles back once the pole push was finished. Ski contact time (CT_{ski}) was calculated using data from the IMUs mounted on the skis. Initial ski contact was defined as the first peak of the pitch angular velocity before a long phase with low angular velocity due to the skis being on the ground, while the terminal ski contact was set as the last negative vertical acceleration peak after the low angular velocity phase. The overall precision for CT_{pole} was 18 ± 21 ms (6.5 ± 11.5%) and for CT_{ski} was 7 ± 13 ms (0.7 ± 1.0%).

Absolute and Relative Pole and Ski Power

The center of mass (CoM) of the body was calculated based on the marker position data from the Oqus measurements [see (10) for details]. The mass properties of body segments were calculated according to de Leva (1996), while CoM velocity was determined by the numerical differentiation of the position data. In skate-style XC skiing, the instantaneous power is generated from poling and ski push-offs. Thus, pole power (P_{pole}) was calculated from pole force (F_{pole}) and CoM velocity (V_{CoM}): $[P_{pole} = F^*_{pole\_x}V_{CoM\_x} + F^*_{pole\_y}V_{CoM\_y} + F^*_{Pole\_z}V_{CoM\_z}]$, with x, y, and z representing components of F_{pole} and V_{CoM} in the forward-backward (x), sideways (y), and vertical (z) directions (Donelan et al., 2002). P_{pole} was calculated independently for each pole and the values for each pole were subsequently summarized. The difference between work rate (P_{cycle}) and average P_{pole} per cycle was interpreted as average ski power (P_{ski}). Relative P_{pole} (%P_{pole}) and relative P_{ski} (%P_{ski}) were calculated as the percentage of the P_{cycle} for each skier, while relative $P_{poleleft}$/$P_{polerigth}$ (%$P_{poleleft}$/%$P_{poleright}$) was calculated as the percentage of the P_{pole} for each skier. One skier's power data for the entire test were missing due to technical issues and were therefore not included in the analysis.

Synchronization and Processing of Data

All continuously derived sensor data, namely, HR, $\dot{V}O_2$, TSI_{leg}, TSI_{arm}, CL, CR, sub-technique, CT_{pole}, CT_{ski}, P_{cycle}, %P_{pole}, %P_{ski}, %$P_{poleleft}$, and %$P_{poleright}$ were synchronized to a common master timeline and compound into one dataset with a 1 Hz resolution before the means were calculated. Start and stop times for treadmill speed and incline, HR, $\dot{V}O_2$, and NIRS data were manually noted during the data collection, whereas the synchronization of IMU-derived data, namely, CL, CR, sub-technique, CT_{pole}, and CT_{ski}, were found by identifying three synchronization jumps from the calibration routine in the IMU data and on video. Reduction to the 1-Hz resolution was performed by calculating the mean for each second of data, except for the NIRS data, for which mean 1-Hz values were calculated over 2 s.

The terrain-dependent fluctuations (TDF) in HR, $\dot{V}O_2$, TSI_{leg}, and TSI_{arm} were defined for each skier as

$$TDF = \frac{\sum_{Lap\ 2}^{Lap\ 7} (\%PeakVal - \%MinVal)}{NumLaps} \tag{1}$$

where %PeakVal and %MinVal is given in % of max level and NumLaps is equal to 6 laps. Note that Lap 1 was excluded from these analyses since this lap starts from rest, which provides physiological values for this lap that deviate from the true fluctuation in metabolic demands.

Time-dependent change in the physiological variables (TDC_{Phys}) from the start to the end of each session was quantified as

$$TDC_{Phys} = \%MeanVal\ Lap\ 7 - \%MeanVal\ Lap\ 2 \tag{2}$$

where %MeanVal is given in % of max level. Note that because Lap 1 starts directly from rest, Lap 2 was used instead of Lap 1.

For the biomechanical parameters, time-dependent change ($TDC_{BioMech}$) was quantified as

$$TDC_{BioMech} = \%MeanVal\ Lap\ 7 - \%MeanVal\ Lap\ 1 \tag{3}$$

where %MeanVal is given in % of max level.

For one of the skiers, the treadmill stopped at Lap 7 at LI. Therefore, time-dependent changes were calculated without the data of that skier, as were other values of variables from Lap 7 for the skier.

The total distance and speed for LI/HI sessions were 5.8/7.5 km and 16.7/21.3 km/h, respectively. These numbers were calculated using the same speeds as in the protocol for Segments 1, 2, and 3; however, for Segment 4, the simulated downhill, 30 $km{\cdot}h^{-1}$ was used for LI and 35 $km{\cdot}h^{-1}$ for HI based on data from a previous field study (7) instead of the protocol-speed (20 $km{\cdot}h^{-1}$) to give more realistic numbers for total distance and average speed. Due to the safety of the skiers, the speed during the simulated downhill was intentionally kept lower than what is normally used in real downhills.

Statistical Analysis

All data were tested for normality using the Shapiro–Wilk test in combination with the visual inspection of data and are presented herein as $M \pm SD$.

A two-way repeated-measures analysis of variance was used to analyze the effect of segment and lap and their interactions on %HR, %$\dot{V}O_2$, TSI_{arm}, TSI_{leg}, and %P_{pole} at LI and HI separately. When significant primary effects were found, Tukey's *post-hoc* analysis was performed to determine pairwise comparisons.

For data that met the assumption of normality, mean values for all variables at LI and HI sessions, including terrain-based fluctuations, biomechanical variables, and power variables for separate sub-techniques both for the entire sessions and in segments, were compared using a paired sample t-test (**Table 2** and **Supplementary Tables 1**, **2**). TSI_{arm}/TSI_{leg}, CT_{pole}/CT_{ski}, %P_{pole}/%P_{ski}, and terrain-based fluctuations in %HR and %$\dot{V}O_2$ were compared using paired t-tests separately for LI and HI data. Non-normally distributed data (i.e., only $P_{poleright}$ in G4 and $P_{poleleft}$ in G4, shown in **Supplementary Table 1**) were compared using a non-parametric Wilcoxon signed-rank test.

A two-way repeated-measures analysis of variance was used to analyze the effect of intensity on time-dependent changes from Lap 1 (i.e., biomechanical and power) or Lap 2 (i.e., physiological) with Lap 7 and their interactions. If main effects were found, pairwise comparisons were done with a paired sample t-test (**Table 2** and **Supplementary Table 1**).

The level of statistical significance was set at $\alpha = 0.05$. All statistical analyses were performed using SPSS version 26.0 (SPSS Inc., Chicago, IL, USA).

RESULTS

In the following sections, the results are presented from three different levels: fluctuations of variables with 1 s resolution (**Figure 2**), overall means for the entire 21 min LI and HI sessions divided and not divided into different sub-techniques (**Table 2** and **Supplementary Table 1**), and means for laps and segments (**Figures 3–5** and **Supplementary Table 2**).

TABLE 2 | Heart rate (HR), oxygen uptake ($\dot{V}O_2$), tissue saturation index (TSI) for the leg (TSI_{leg}) and arm (TSI_{arm}), power variables, rate of perceived exertion (RPE), and blood lactate (BLa) for the low-intensity (LI) vs. high-intensity (HI) sessions, with means (*M*), standard deviations (*SD*), and *p*-values.

		LI		HI			HI–LI
Period: Laps 1–7	***N***	***M***	***SD***	***M***	***SD***	***p***	**Δ (%Δ)**
Mean %HR [in % of HR_{max}]	9	74.1	3.1	89.7	2.5	<0.01	15.5 pp
Mean %$\dot{V}O_2$ [in % of $\dot{V}O_{2max}$]	9	58.3	2.4	79.4	3.5	<0.01	21.0 pp
Mean $\dot{V}O_2$ [mL/kg/min]	9	41.1	0.8	55.9	1.7	<0.01	14.8 (36%)
Mean TSI_{leg} [%]	9	64.6	3.8	58.3	6.7	<0.01	−6.3 pp
Mean TSI_{arm} [%]	9	52.6	7.1	48.8	9.0	0.03	−3.8 pp
Whole-body RPE	9	12.7	1.2	17.2	1.5	<0.01	4.5 (35%)
Upper-body RPE	9	12.6	1.2	17.3	1.7	<0.01	4.7 (37%)
Lower-body RPE	9	12.8	1.2	17.2	1.5	<0.01	4.4 (34%)
BLa [mmol/L]	9	1.3	0.3	11.1**	2.1	<0.01	9.8 pp
Peak %HR [in % of HR_{Max}]	9	81.4	3.4	98.4	2.0	<0.01	17.0 pp
Peak %$\dot{V}O_2$* [in % of $\dot{V}O_{2max}$]	9	75.9	4.9	98.6	3.2	<0.01	22.7 pp
%HR fluctuation [pp]	9	17.7	2.7	12.2	3.3	<0.01	−5.3 pp
%$\dot{V}O_2$ fluctuation [pp]	9	31.7	4.4	33.0	1.7	0.50	1.3 pp
%TSI_{leg} fluctuation [pp]	9	12.6	3.3	24.3	9.3	<0.01	11.7 pp
%TSI_{arm} fluctuation [pp]	9	23.9	6.1	33.4	13.9	0.04	9.5 pp
Period: Laps 1, 3, 5, and 7		**LI**		**HI**			
P_{cycle} [Watt]	8	205	15	291	21	<0.01	85.9 (42%)
%P_{pole} [in % of P_{cycle}]	8	55.7	5.1	57.6	5.2	0.31	1.9 pp
%P_{ski} [in % of P_{cycle}]	8	44.3	5.1	42.4	5.2	0.31	−1.9 pp
%$P_{poleleft}$ [in % of P_{pole}]	8	47.9	5.6	47.6	3.5	0.88	−0.3 pp
%$P_{polerigth}$ [in % of P_{pole}]	8	52.0	5.0	51.3	3.6	0.88	−0.7 pp
Change: Lap 7–Lap 2		**LI**		**HI**			
%HR [in % of HR_{max}]	8	2.3	2.0	7.8*	1.1	<0.01	5.5 pp
%$\dot{V}O_2$ [in % of $\dot{V}O_{2max}$]	8	−0.4	0.7	1.1	2.7	0.34	1.5 pp
TSI_{leg} [%]	8	−2.1	1.6	−1.2	2.4	0.53	0.8 pp
TSI_{arm} [%]	8	−0.6	1.1	−2.9	2.0	0.05	−2.4 pp
Change: Lap 7–Lap 1							
%P_{pole} [in % of P_{cycle}]	7	−6.6*	2.5	−7.7*	4.5	0.48	−1.1 pp
%P_{ski} [in % of P_{cycle}]	7	6.6*	2.5	7.7*	4.5	0.48	1.1 pp
%$P_{poleleft}$ [in % of P_{pole}]	7	−0.4	1.5	0.5	1.5	0.24	0.9 pp
%$P_{polerigth}$ [in % of P_{pole}]	7	0.4	1.5	−0.5	1.5	0.24	−0.9 pp

The time-dependent change from Lap 2 to Lap 7 for HR, $\dot{V}O_2$, and TSI variables and from Lap 1 to Lap 7 for power variables are shown as well.

Note. pp = percentage points. HR_{max} = the highest heart rate (beats per minute) measured during the protocol. $\dot{V}O_{2max}$ = the highest 30-s moving average (based on 10-s mixing chamber values) during the maximal incremental test, Δ = difference in mean value between HI and LI, %Δ = percentage of difference in mean value between HI and LI relative to LI, P_{cycle} = mean power for cycle, %P_{pole} = relative power from poling, %P_{ski} = relative power from ski push-offs, %$P_{poleleft}$ = relative power from left pole, %$P_{polerigth}$ = relative power from right pole, %HR/%$\dot{V}O_2$/%TSI fluctuation = mean value of the difference between maximum and minimum values for each lap, with Lap 1 excluded due to starting from rest. Non-significant numbers are highlighted in light gray.

**Significant time-dependent change ($p < 0.05$): HR, $\dot{V}O_2$, TSI_{arm}, and TSI_{leg} Lap 7–Lap 2, power: Lap 7–Lap 1.*

***BLa was measured after HI and the all-out sprint.*

Physiological Responses

Fluctuations in physiological variables for LI and HI according to the set inclines and workloads in LI and HI are shown in **Figure 2**, while values averaged overlaps and segments for the same variables are displayed in **Figure 3**.

Significant interaction effects between lap and segment were found at both LI and HI for %$\dot{V}O_2$ and at HI for %HR (all p <. 01) but not at LI for %HR ($p = 0.88$). At both LI and HI, significant main effects of segment occurred for both %HR and %$\dot{V}O_2$ (all $p < 0.01$), as shown in **Figure 3A**. At LI, %HR and %$\dot{V}O_2$ did not differ between Segments 2 (2% uphill) and 3 (12% uphill) (%HR: $p = 0.88$, %$\dot{V}O_2$: $p = 0.83$) and were higher than in the other segments (all $p < 0.01$). In addition, mean values for Segments 1 (5% uphill) and 4 (downhill) did not differ for %HR ($p = 0.15$), while %$\dot{V}O_2$ for Segment 1 was lower than for Segment 4 ($p < 0.01$). At HI, Segments 2 and 4 did not differ in %HR ($p = 0.36$), which was higher than in Segment 1 and lower than in Segment 3 (both $p < 0.01$). Concerning %$\dot{V}O_2$, however, all segments differed (all $p < 0.01$). For %HR, interaction effects between intensity and time-dependent changes (from Lap 2 to

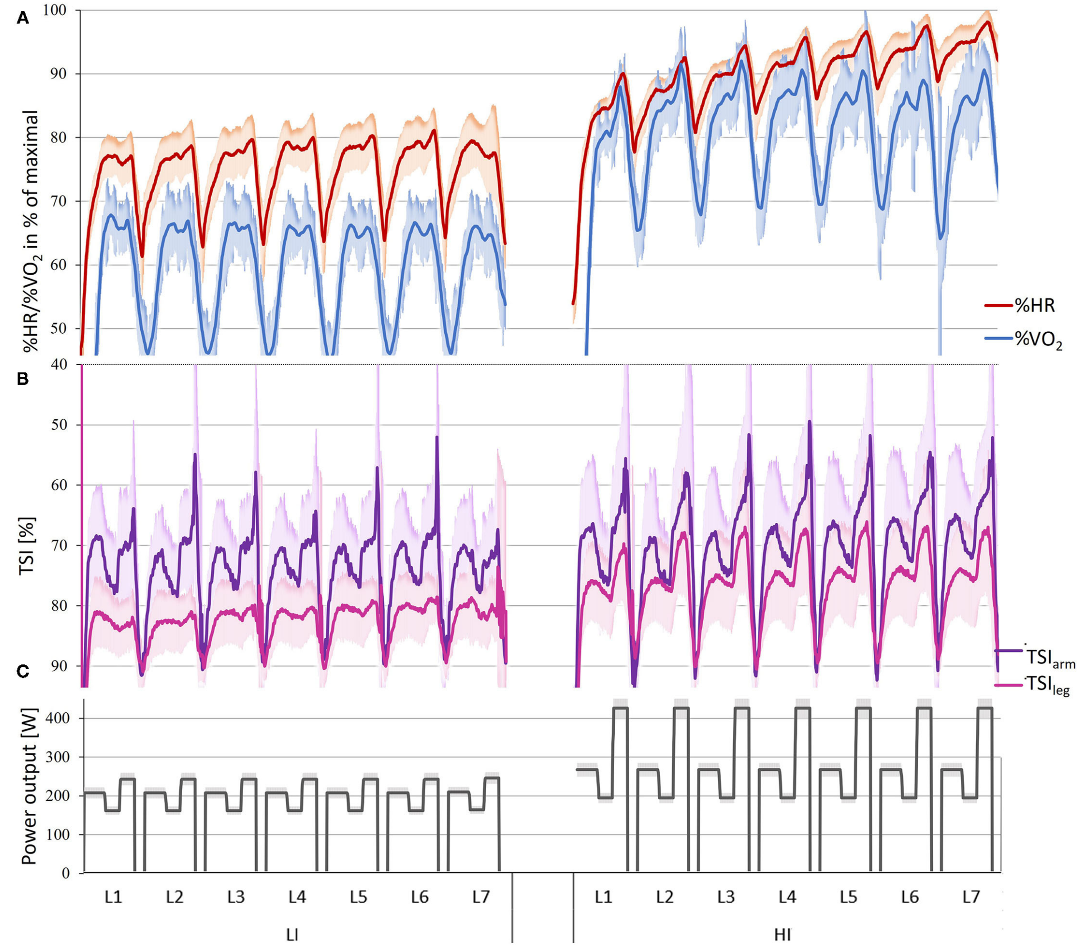

FIGURE 2 | (A) Relative heart rate (%HR) and relative oxygen uptake (%$\dot{V}O_2$ 30 s moving average), **(B)** tissue saturation index (TSI) for the vastus lateralis in the right leg (TSI$_{leg}$ and the long head of the triceps brachii in the right arm (TSI$_{arm}$), and **(C)** power output for the LI and HI sessions (*M* ± *SD*) with 1-Hz resolution. For TSI, the vertical axis is reversed.

Lap 7) as well as effects for intensity and time-dependent time were found (all $p < 0.01$), while for %$\dot{V}O_2$, significant effects were only found for intensity ($p < 0.01$). At LI, a significant main effect of the lap was found for %$\dot{V}O_2$ and %HR (both $p < 0.01$). However, only Lap 1 differed significantly from the other laps (all $p < 0.01$), for it began from the rest (all other $p > 0.30$). At HI, both %$\dot{V}O_2$ and %HR had significant main effects in relation to lap (both $p < 0.01$). Only in Lap 1 did %$\dot{V}O_2$ significantly differ from the other laps. However, for %HR, HR slowly increased toward the end of the session (**Table 2**).

At LI and HI, no significant interaction effects between lap and segment were found for TSI$_{arm}$ or TSI$_{leg}$ (all $p = 1.00$). However, significant main effects of the segment were found for both variables ($p < 0.01$) (**Figure 3B**). For neither TSI$_{arm}$ nor TSI$_{leg}$, significant main effects were not found between intensity and time-dependent changes from Lap 2 to Lap 7 (all $p > 0.57$). Although no significant main effect of the lap was found for TSI$_{arm}$ at LI or HI or for TSI$_{leg}$ at HI ($p = 1.00$), a significant main effect of the lap in Lap 1 was found for TSI$_{leg}$ ($p = 0.04$), which during Lap 6 was less than during Lap 1 ($p = 0.05$).

Mean physiological variables at LI and HI are shown in **Table 2**. Due to the higher workload at HI than at LI, %HR, %$\dot{V}O_2$, RPE and BLa were higher at HI while TSI$_{arm}$ and TSI$_{leg}$ were lower. Terrain-based fluctuations in %VO$_2$ did not differ between HI and LI (∼32%-points, $p = 0.50$). By comparison, %HR fluctuated less than %$\dot{V}O_2$ at HI than at LI (-12.2%-points, $p < 0.01$) and displayed a time-dependent increase at HI

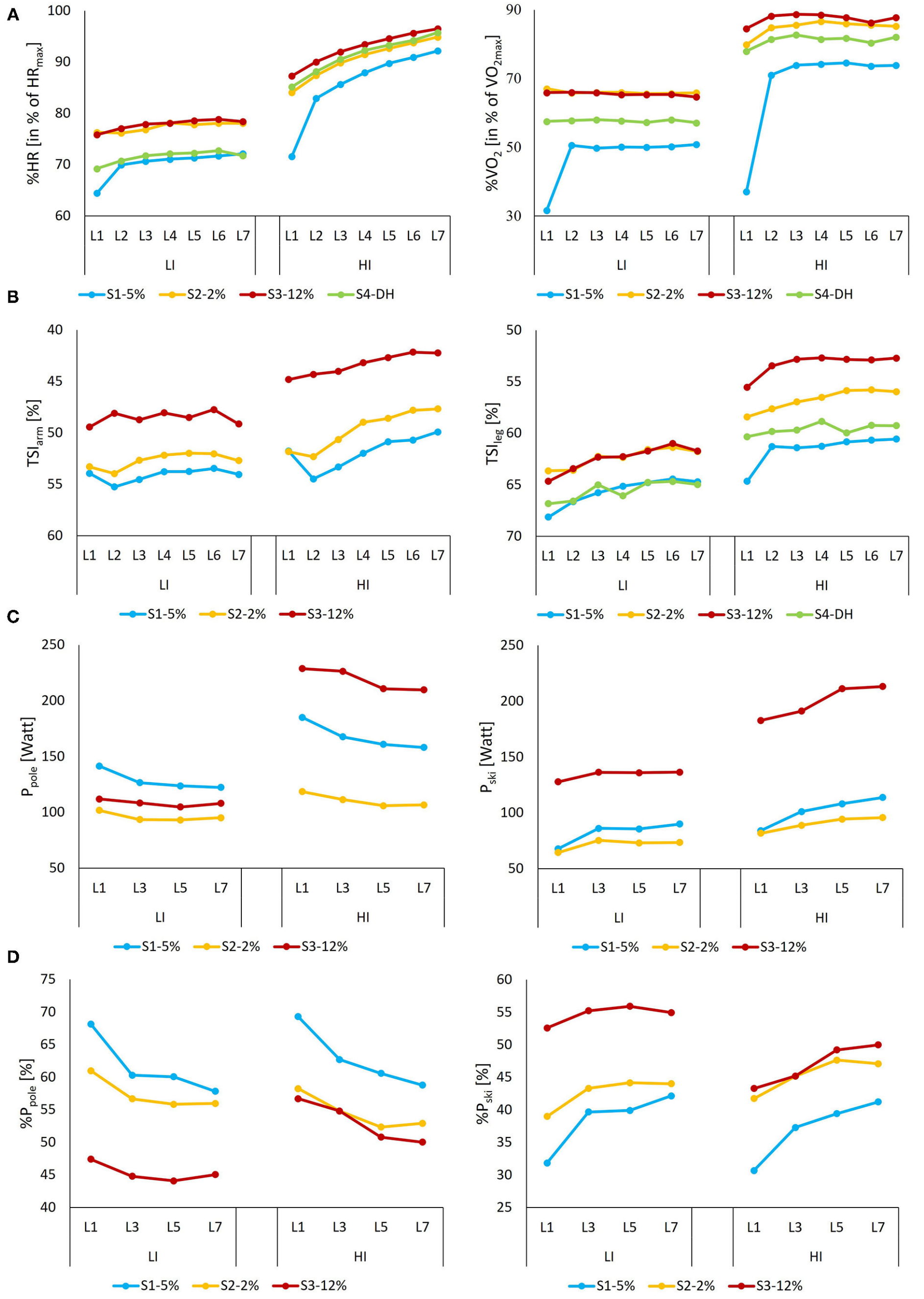

FIGURE 3 | (A) %HR and %$\dot{V}O_2$, **(B)** TSI_{arm} and TSI_{leg}, **(C)** absolute and **(D)** relative power for pooling (P_{pole} and ski push-offs (P_{ski} for each segment (S1–S4) as a function of the lap (i.e., L1–L7) during LI and HI sessions. For TSI, the vertical axis is reversed, and TSI_{arm} in the simulated downhill segment (i.e., S4) is not shown due to excessive movement noise in the signal when the skiers grabbed the rope.

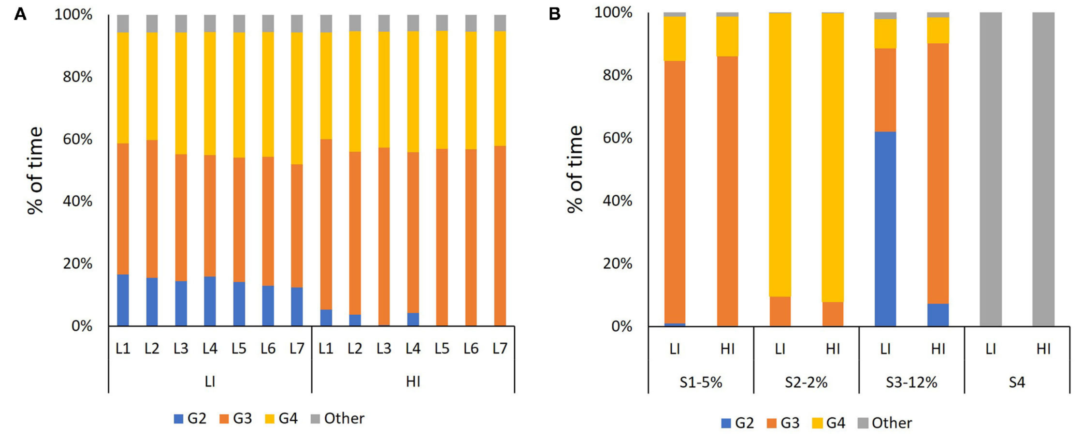

FIGURE 4 | Distribution of sub-techniques, in the percentage of the time, **(A)** as a function of the lap (i.e., L1–L7) and **(B)** as a function of segment (i.e., S1–S5), in the LI and HI sessions.

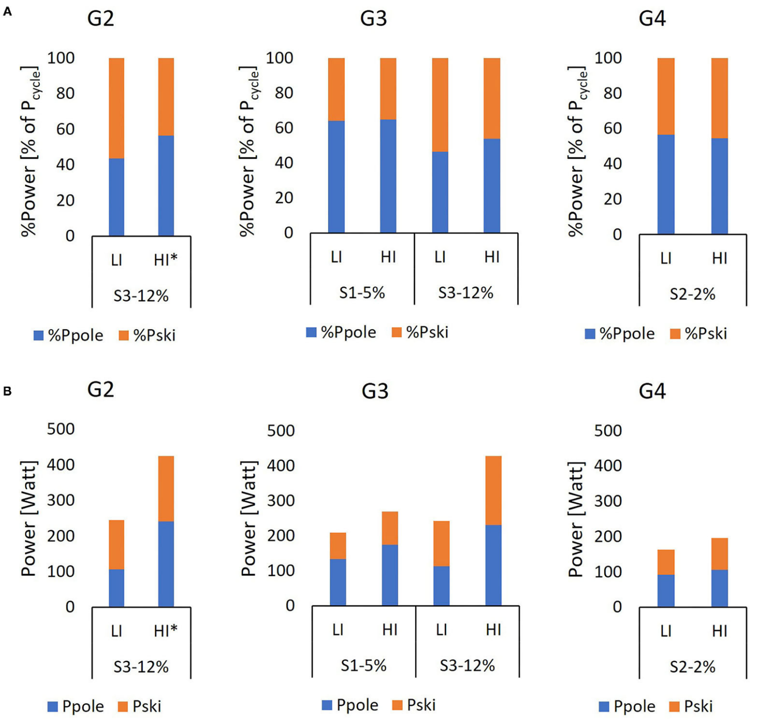

FIGURE 5 | Mean values for **(A)** relative and **(B)** absolute pole power (%P_{pole}, P_{pole}) and ski power (%P_{ski}, P_{ski}) during the LI and HI sessions for all sub-techniques and segments (i.e., S1–S3) for all skiers (*n* = 8) with power data. During the HI session, G2 was used only by five skiers, one of whom was missing power data, hence the small sample.

(7.8%-points, $p > 0.01$). Both TSI_{arm} and TSI_{leg} terrain-based fluctuations were greater at HI than LI (TSI_{arm}: 9.5%-points, TSI_{leg}: 11.7%-points, both $p < 0.01$). Compared with TSI_{leg}, TSI_{arm} had high terrain-based fluctuations (LI: 11.3%-points, HI: 9.1%-points, $p < 0.05$) and low mean values both at LI (-12%-points, $p < 0.01$) and HI (-9.5%-points, $p < 0.01$). However, TSI_{leg} decreased more than TSI_{arm} (2.4%-points, $p = 0.05$) from LI to HI.

Sub-technique Selection and Biomechanical Responses

The selection of sub-techniques during the different laps and segments at LI and HI is displayed in **Figure 4**, while corresponding temporal patterns as a function of a sub-technique, segment, and/or lap at both LI and HI are provided in **Figure 6** and **Supplementary Tables 1**, **2**.

At LI, the skiers primarily selected G3 during Segment 1, G4 during Segment 2, and G2 during Segment 3 (**Figure 4B** and **Supplementary Table 1**). At HI, the same pattern emerged, with the primary difference being the greater use of G3 during Segment 3 ($p < 0.05$). Neither CL nor CR changed significantly from Lap 1 to Lap 7 for any of the sub-techniques (all $p > 0.05$), as shown in **Figure 5**. For all sub-techniques, CL was longer and CR was higher at HI than at LI (**Figures 6A,B** and **Supplementary Tables 1**, **2**). The relative change from LI to HI was greater for CL than for CR in both overall (**Supplementary Table 1**) and by segment (**Supplementary Table 2**).

At both LI and HI, CT_{pole}, CT_{ski}, $\%CT_{pole}$, and $\%CT_{ski}$ depended on the used sub-technique and segment, with CT_{pole} being shorter than CT_{ski} for all sub-techniques (**Figures 6D,E** and **Supplementary Tables 1**, **2**). At HI during G4, CT_{pole} showed a time-dependent change from Lap 1 to Lap 7, with a 6.7% longer poling time ($p < 0.01$). For the other sub-techniques and CT_{ski}, no significant change arose (all $p > 0.05$).

Overall, CT_{pole}, $CT_{ski,}$ and $\%CT_{pole}$ were lower for all sub-techniques at LI than at HI (**Supplementary Table 1**). However, there was no change in $\%CT_{ski}$ between G2 and G3 (**Supplementary Table 1**). When divided into segments, both CT_{pole}, CT_{ski}, $\%CT_{ski}$, and $\%CT_{ski}$ were lower at LI than at HI in all cases except for $\%CT_{ski}$ during G2 in Segment 3 (**Supplementary Table 2**). Added to that, for HI, CT_{pole} was shorter than CT_{ski} for all sub-techniques (**Supplementary Tables 1**, **2**).

Power Distribution

The relative and absolute ski and pole power during each segment and sub-technique are displayed in **Figure 5**, with the relative power for each segment as a function of lap number shown in **Figure 6C**.

At LI and HI, no significant interaction effects between lap and segment were found in overall $\%P_{pole}$ or $\%P_{ski}$ (= 100%–$\%P_{pole}$) (both $p > 0.86$). However, significant main effects were found for segment (both LI and HI $p < 0.01$). Beyond that, $\%P_{pole}$ in Segments 1 and 2 at LI did not differ ($p = 0.69$) and was higher than in Segment 3 (all $p < 0.01$), while at HI $\%P_{pole}$ in Segments 2 and 3 did not differ ($p = 0.61$) and was less than in Segment 1 (all $p < 0.01$). In addition, $\%P_{pole}$ was significantly higher than $\%P_{ski}$ (11.5%-points, $p = 0.02$). No significant main effects were found for $\%P_{pole}$ and $\%P_{ski}$ between intensity and time-dependent changes from Lap 2 to Lap 7 ($p = 0.69$). However, significant effects were found for the time-dependent changes ($p < 0.01$). At both LI and HI, a significant main effect of the lap was found for $\%P_{pole}$, with a time-dependent change toward relatively more power from the ski push-offs (i.e., Lap 7 – Lap 1), both overall ($p < 0.01$, **Table 2**), and for G3 and G4 separately ($p < 0.01$, **Figure 5A**).

Overall mean values for $\%P_{pole}$ and $\%P_{ski}$ did not differ between LI and HI (**Table 2**), and $\%P_{pole}$ was significantly higher than $\%P_{ski}$ at both LI (11.5%-points, $p = 0.02$) and HI (15.2 %-points $p < 0.01$). $\%P_{pole}$ depended on sub-technique and segment (**Figure 5A** and **Supplementary Tables 1**, **2**).

The relative contribution of power from the right and left poles differed between individuals independent of sub-technique and incline and did not show the main effects of laps during any sub-techniques at LI or HI ($p > 0.05$), as shown in **Table 2** and **Supplementary Table 1**.

DISCUSSION

The primary purposes of our study were to investigate physiological and biomechanical responses to LI and HI roller ski skating on varying terrain and to compare the responses between training intensities. Here, we provide a novel understanding of the complex physiological and biomechanical stimuli provided by LI and HI training in XC skiing by highlighting three primary findings. First, both LI and HI training on varying terrain induced large terrain-dependent fluctuations in HR, $\dot{V}O_2$, and muscle oxygen saturation. In addition, the power distribution generated by poles and skis depended on the sub-technique employed both for LI and HI, with a time-dependent shift toward gradually more power coming from the ski push-off from the start to the end of each session within all sub-techniques. Second, terrain-based fluctuations in $\dot{V}O_2$ were similar at LI and HI, whereas HR fluctuated less at HI and demonstrated a time-dependent increase in HR. The arm muscle vs. leg muscle oxygen saturation ratio changed, and an interaction effect arose between segments amid increased intensity from LI to HI. Third, the G2 sub-technique was employed more than G3 on the steepest uphill section at LI than at HI, while CL increased two to three times more than CR, and CT_{pole} decreased more than CT_{ski} from LI to HI when compared in the same terrain.

Both the LI and HI sessions were performed on varying terrain and induced terrain-dependent fluctuations in %HR and $\%\dot{V}O_2$, thereby exemplifying the interval-based cardiovascular and muscular loading during XC skiing. This clearly differs from training at similar intensities in most other exercise modalities or endurance sports in which loading is more stable (Sandbakk et al., 2021). The simultaneous measurements of $\%\dot{V}O_2$ and %HR show that the timing of the peak values (i.e., in or after the steepest uphill ascents) of $\%\dot{V}O_2$/%HR were independent of intensity. However, the decrease in %HR during the simulated

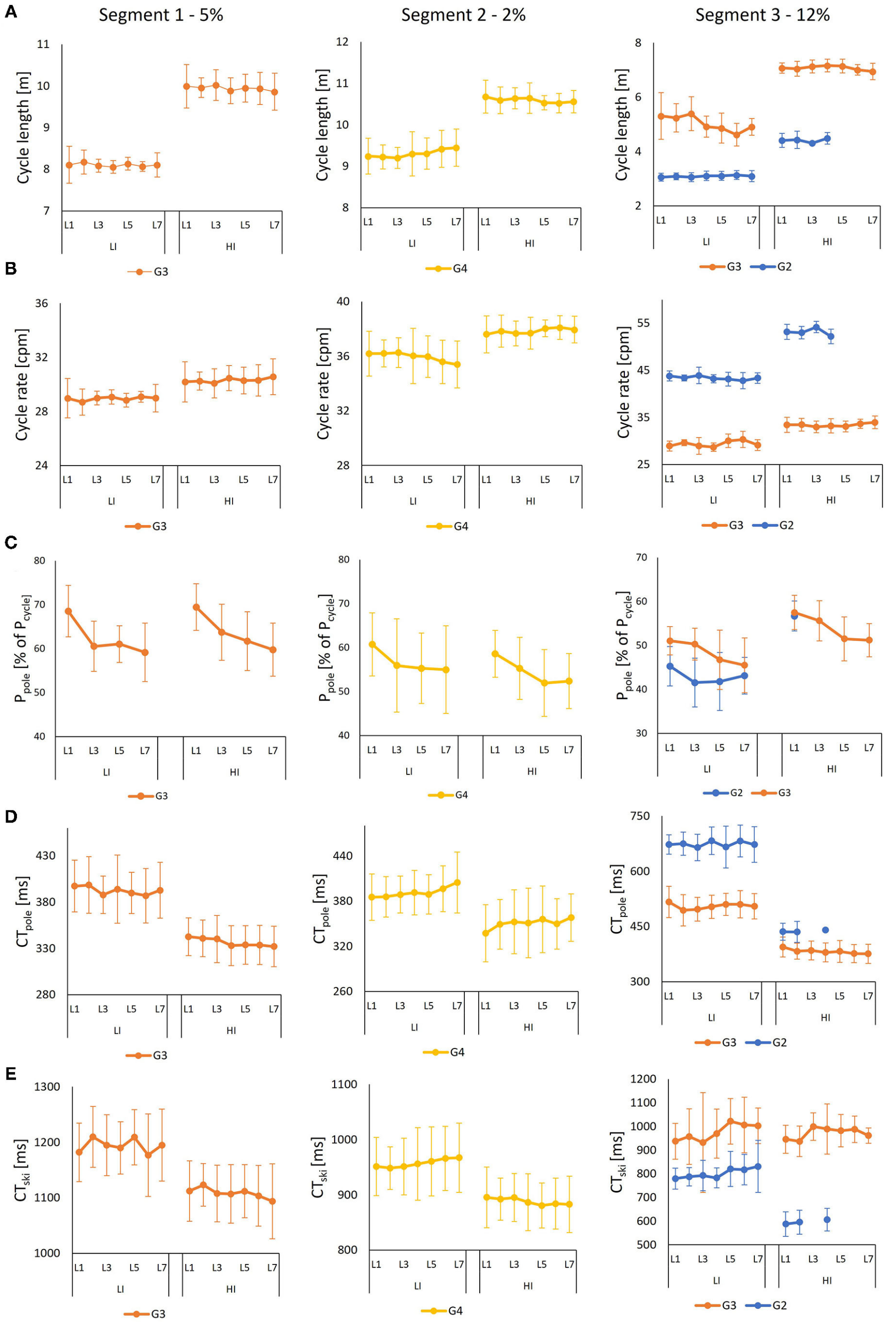

FIGURE 6 | (A) Cycle length (CL), **(B)** cycle rate (CR, in cycles per minute, cpm), **(C)** relative power contribution from pooling (in % of total power for each cycle), **(D)** contact time for pole (CT_{pole}), and **(E)** contact time for ski (CT_{ski}), all variables as a function of the lap (i.e., L1–L7) during the LI and HI sessions for each segment

(Continued)

FIGURE 6 | ($M \pm SD$). Power from ski push-offs is given as $\%P_{ski} = 100\%–\%P_{pole}$. Power contribution was measured only for odd lap numbers and was not available for one of the skiers. If the skier spent <6 s on a particular sub-technique in one segment or lap, then it was excluded from the analysis. During the HI sessions, G2 was used only by five skiers, one of whom was missing power data, hence the small sample.

downhill segment was less and delayed compared with the larger (and faster-responding) decrease in $\%\dot{V}O_2$. Those differences also depended on intensity, with the decrease in %HR during downhills in HI being less than at LI, thereby confirming the results of several other studies (Gløersen et al., 2018; Karlsson et al., 2018; Solli et al., 2018; Haugnes et al., 2019). Such results can be explained by skiers often driving the intensity up to and above $\dot{V}O_{2max}$ in uphill ascents. Indeed, in our study, the skiers reached 98.4% of HR_{max} (range: 94.3–100%) and 98.6% of $\dot{V}O_2$max (range: 93.2–102.1%), and the subsequent oxygen deficit resulted in a reduced and delayed HR recovery (Gløersen et al., 2020). The significant time-dependent change in %HR at HI also differed from the $\%\dot{V}O_2$ response, which remained stable throughout the LI and HI sessions except from Lap 1, at which the $\%\dot{V}O_2$ was lower due to the starting of skiers from rest. Altogether, those findings have important implications for the interpretation of %HR during training and competitions, which is often used as a real-time proxy for $\%\dot{V}O_2$ during non-steady-state exercises such as XC skiing (Solli et al., 2018; Haugnes et al., 2019). Thus, the degree to which %HR can be used to accurately indicate $\%\dot{V}O_2$ during interval-like or even continuous exercise clearly seems to depend on duration, intensity, and fluctuations in intensity (Boulay et al., 1997; Bot and Hollander, 2000; Tucker et al., 2006; Kolsung et al., 2020). Since HR has limitations in its ability to reflect metabolic intensity in XC skiing, a practical solution may be to complement HR measures with perceived exertion, in addition to analyses of blood lactate concentration on selected sessions, to decide exercise intensity during training.

Complementary to HR and $\dot{V}O_2$ measurements, muscle oxygen saturation, measured by the TSI in the arms (triceps brachii) and legs (vastus lateralis), provide valuable indications about the local metabolism of the working muscles. Similarly, the TSI-values also fluctuated according to the terrain both at LI and HI, with only slight delays in kinetics. Similar fluctuations in muscle oxygen saturation during interval-like HI training were found when oxygen saturation in working muscles (i.e., biceps brachii, triceps brachii, latissimus dorsi, and vastus lateralis) was measured during successive upper-body sprints (Sandbakk et al., 2015a). In our study, TSI values for both arms and legs decreased significantly from LI to HI. However, the terrain-dependent fluctuations in oxygen saturation in the arms differed from the corresponding measurements in the legs and were not associated with the amount of power generated by the arms vs. legs (**Figures 3B–D**). That finding aligns with results from a recent case study during a long-term competition in double poling, in which TSI measures for the triceps brachii showed larger terrain-based fluctuations than for the vastus lateralis (Stöggl and Born, 2021). Our findings thereby indicate that the desaturation of the muscles depends more on whole-body stress (i.e., %HR and $\%\dot{V}O_2$) than the contribution from specific muscles, as previously suggested (Im et al., 2001). However, studies focusing more specifically on this issue are needed to conclude.

Mean TSI_{arm} was less than mean TSI_{leg} at both LI and HI, which indicates less oxygen saturation in the arms than the legs at both intensities. That finding aligns with results from two other studies in which elite skiers performed diagonal stride (Björklund et al., 2010) and double poling (Stöggl et al., 2013). Interestingly, the mean value for TSI_{leg} decreased more than that for TSI_{arm} from LI to HI, thereby indicating that for XC skiing the muscular load of the arms seems to be more independent of the overall internal and external intensity than the muscular load of the legs. That finding may have implications for understanding the specific muscular workload of LI training on varying terrain, by indicating that skiers can experience a high muscular training load in the arms at LI as well as at HI.

For both LI and HI, the skiers adapt their technique to the workload by generating more power from poling than ski push-offs, which is in line with the TSI measurements showing that TSI_{arm} was lower than TSI_{leg} at both LI and HI. Also, the distribution of pole and ski power seems less dependent on intensity than on sub-technique and thus incline. At LI, for example, we found more ski than pole power in the steep uphill ascent, both in G2 and G3, whereas more pole power was produced in G3 during the moderate incline. In addition, the findings related to G3, with more pole power produced at lower inclines, align with results from a study of the distribution of power generated by the arms and legs during double poling (Danielsen et al., 2019), in which the authors found that double poling at a 12% incline required less power from the arms than at a 5% incline, partly due to less advantageous working conditions for the arms with shorter poling times and a reduced angle between the arms and the ground at steeper uphill's. Because G3 and double poling have synchronized, highly similar arm movements, the same could be assumed to apply to our findings; that is, that less advantageous working conditions for the arms are causing the reduced power contribution from the arms at higher inclines. However, those aspects require further examination by using a specifically designed experimental setup.

Independent of intensity and sub-technique, the relative pole and ski power distribution gradually changed, with a higher contribution of ski power toward the end of the session. The change in power distribution could have been done intentionally to save the legs toward the end, or else because the skiers became more fatigued in the upper than in the lower body and therefore gradually generated more ski power. That compromise between generating arm (i.e., pole) and leg (i.e., ski) propulsion during skiing likely depends on individual resources and on how skiers pace their arms and legs, an aspect that requires more attention in future research. However, the change in power distribution did not influence CL or CR, which varied according to incline, speed, and sub-technique used but showed the same pattern within each sub-technique for all laps.

At LI, the skiers primarily selected G3 in the moderately uphill segment, G4 in the flat terrain, and G2 in the steep uphill ascent.

HI had a similar pattern in sub-technique distribution as LI, with the exception of the steepest uphill (12% incline), where the skiers used more G3 and less G2 at HI than at LI. Accordingly, our findings indicate that skiers apply the same sub-techniques independently of training intensity across flat, and moderately uphill terrain, which is also the case for downhill terrain. A practical implementation of that finding could be to perform LI sessions on less strenuous terrain to enable the use of the same sub-techniques used during HI sessions with relatively little effort. Furthermore, it seems important to prioritize training in G3 at high speeds during steep uphill ascents as part of HI or sprint sessions, because that skill is more challenging to practice at LI.

Both macro and micro-kinematic variables depended on sub-technique and incline, as previously found in other studies (Nilsson et al., 2004; Stöggl and Müller, 2009; Sandbakk et al., 2012). CL and CR increased with higher intensity and speed, with CL increasing 2–3 times more than CR from LI to HI in most cases. That observation contrasts with past observations, in which CR has been identified as the primary driver of speed at moderate to high speeds (Nilsson et al., 2004; Stöggl and Müller, 2009), but agrees with other findings that both CR and CL did increase with speed (Sandbakk et al., 2012, 2015b). A practical takeaway from our findings is that skiers, to simulate competition-relevant CLs could include periods in their LI training during which they intentionally aim to ski with a lower CR than normal, as done in other sports, including road cycling (Aasvold et al., 2019). Such low-frequency training may be particularly relevant in relatively flat (or gentle downhill) terrain where CL has been shown as the main driver of increased speed.

Coinciding with the increase in CL and CR with speed, CT_{pole} and CT_{ski} decreased from LI to HI within all sub-techniques. Although that decrease in CT_{pole} is natural because CT_{pole} is highly dictated by speed, CT_{ski} can be maintained at a higher speed by angling the skis forward. However, in future studies, CT_{ski} should be divided into push-off and gliding (i.e., no push-off) time, where it would be expected that glide time increase with speed while ski push-off time remains more constant, in order to provide a more nuanced understanding of how this variable change with intensity. For both poles and skis, $\%CT_{pole}$ and $\%CT_{ski}$ also decreased from LI to HI. However, that change was far smaller than the change in CT_{pole} and CT_{ski}. Although the power output of skiers is higher, skiers are forced to produce the power over shorter periods, with longer relative recovery times within a cycle, at higher intensities. That trend means altered muscle contraction dynamics and requires the ability to produce high power over a short time.

STRENGTHS AND LIMITATIONS

The advantage of performing our study indoors while participants roller skied on a treadmill was that both physiological and biomechanical variables could be measured more accurately than while outdoors on snow. However, the differences between our setup and real-life situations when skiing outdoors require interpreting our results with caution. In addition, speed was preset for each incline at LI and HI, and even though the incline–speed combinations were carefully selected, the results could have differed if the skiers had freely chosen their speeds. Accordingly, the design of our study allowed us to investigate the underlying physiological and biomechanical mechanisms while skiing at LI and HI and thereby increase the generalizability of our results. A tradeoff, however, was a limitation in ecological validity. Even so, our protocol reflects the reality of elite skiers, who often perform LI and HI training together in groups.

CONCLUSIONS

Both LI and HI XC skiing on varying terrain induce large terrain-dependent physiological and biomechanical fluctuations, similar to the patterns found during HI XC skiing. The primary differences between training intensities were the time-dependent increase in HR, reduced relative oxygen saturation in the legs compared to the arms, and the greater use of G3 on steep uphill terrain at HI, whereas sub-technique selection, CR, and pole vs. ski power distribution were similar across intensities on flat and moderately uphill terrain. In addition, the distribution between ski and pole power, including the gradual time shift toward more ski power from the start to the end of each session, seemed to depend more on sub-technique and incline than intensity. Overall, our findings illustrate unique physiological and biomechanical responses when XC skiing in varying terrain that coaches and athletes should be aware of when planning LI and HI endurance training. Accordingly, coaches should carefully choose intensity and terrain based on the specific development goal for each session. For example, it might be beneficial to prioritize less strenuous terrain during LI sessions to enable the employment of similar sub-techniques but with less effort than for HI sessions. Beyond that, the findings provide a good starting point for future studies, both for delving deeper into those mechanisms and opens for more applied approaches performed outdoors in future studies.

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/s.

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

DN, JD, and KS conducted data collection. TS, ØS, and JK prepared the manuscript. JD calculated power distribution. JK synchronized and facilitated the sensor data. FM developed the model for extracting CT_{pole} and CT_{ski}. ØS provided expert knowledge in the field and was responsible for designing the experiment. TS developed the model for cycle detection and sub-technique classification, explored and analyzed the data, constructed figures and tables, and was responsible, together with ØS, for finalizing the manuscript. All authors contributed to the overall concepts, protocol, sensor setup, and framework presented in the manuscript, as well as to its revision and ultimate approval.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2021.741573/full#supplementary-material

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Paper 2

frontiers in Physiology

ORIGINAL RESEARCH
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Physiological and Biomechanical Determinants of Sprint Ability Following Variable Intensity Exercise When Roller Ski Skating

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The most common race format in cross-country (XC) skiing is the mass-start event, which is under-explored in the scientific literature. To explore factors important for XC skiing mass-starts, the main purpose of this study was to investigate physiological and biomechanical determinants of sprint ability following variable intensity exercise when roller ski skating. Thirteen elite male XC skiers performed a simulated mass-start competition while roller ski skating on a treadmill. The protocol consisted of an initial 21-min bout with a varying track profile, designed as a competition track with preset inclines and speeds, directly followed by an all-out sprint (AOS) with gradually increased speed to rank their performance. The initial part was projected to simulate the "stay-in-the-group" condition during a mass-start, while the AOS was designed to assess the residual physiological capacities required to perform well during the final part of a mass-start race. Cardiorespiratory variables, kinematics and pole forces were measured continuously, and the cycles were automatically detected and classified into skating sub-techniques through a machine learning model. Better performance ranking was associated with higher VO_{2Max} (r = 0.68) and gross efficiency (r = 0.70) measured on separate days, as well as the ability to ski on a lower relative intensity [i.e., $\%HR_{Max}$ (r = 0.87), $\%VO_{2Max}$ (r = 0.89), and rating of perceived exertion (r = 0.73)] during the initial 21-min of the simulated mass-start (all p-values < 0.05). Accordingly, the ability to increase HR (r = 0.76) and VO_2 (r = 0.72), beyond the corresponding values achieved during the initial 21-min, in the AOS correlated positively with performance (both $p < 0.05$). In addition, greater utilization of the G3 sub-technique in the steepest uphill ($r = 0.69$, $p < 0.05$), as well as a trend for longer cycle lengths (CLs) during the AOS ($r = 0.52$, $p = 0.07$), were associated with performance. In conclusion, VO_{2Max} and gross efficiency were the most significant performance-determining variables of simulated mass-start performance, enabling lower relative intensity and less accumulation of fatigue before entering the final AOS. Subsequently, better performance ranking was associated with more utilization of the demanding G3 sub-technique in the steepest

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uphill, and physiological reserves allowing better-performing skiers to utilize a larger portion of their aerobic potential and achieve longer CLs and higher speed during the AOS.

Keywords: cross-country skiing, gross efficiency, skiing technique, maximal oxygen consumption, inertial measurement unit, Near-infra red spectroscopy, physiological determinants, biomechanical determinants

INTRODUCTION

Cross-country (XC) skiing is a physiologically and technically demanding endurance sport where speed, work rate, and energy expenditure fluctuate with the constantly changing terrain (Andersson et al., 2010, 2016; Sandbakk et al., 2011; Sandbakk and Holmberg, 2014; Bolger et al., 2015). The variation between relatively short sections of uphill, flat and downhill terrain challenge XC skiers to alternate between different sub-techniques with varying contributions from leg and arm work within the two main styles, skating and classic (Seeberg et al., 2017; Solli et al., 2018; Tjønnås et al., 2019).

Accordingly, successful XC skiing requires a high maximal oxygen uptake (VO_{2Max}), as well as the ability to reach a high peak oxygen uptake (VO_{2Peak}) and to ski efficiently within the different sub-techniques (Sandbakk and Holmberg, 2017). Since XC skiers generate particularly high work rates on uphill terrain (Sandbakk et al., 2012a; Andersson et al., 2016; Sandbakk and Holmberg, 2017; Haugnes et al., 2019a), pushing the metabolic demands considerably above those required to elicit VO_{2Max}, XC skiing additionally requires sufficient levels of anaerobic capacity and the ability to recover and reproduce anaerobic power during competitions (Losnegard et al., 2012; Gløersen et al., 2018, 2020; Karlsson et al., 2018; Losnegard, 2019).

Efficient skiing in such constantly changing terrain requires frequent shifts between the different sub-techniques and inherent regulation of cycle length (CL) and cycle rate (CR; Pellegrini et al., 2013; Solli et al., 2018). Previous research has shown that faster skiers use more demanding sub-techniques in steeper terrain than slower skiers (Andersson et al., 2010; Marsland et al., 2017). Additionally, while more efficient skiers obtain longer CL (Sandbakk et al., 2010, 2012a,b, 2013; Åsan Grasaas et al., 2014), fast skiing also requires the ability to employ rapid cycles when accelerating at the start, during breakaway attempts and when sprinting at the finish of races (Haugnes et al., 2019b). In this context the understanding of how skiers regulate the power contributions from poles and skis to generate the required propulsion, and how this affects the oxygenation of muscles in arms and legs is unclear, especially in the skating technique.

The influence of the above-mentioned performance-determining variables on performance in XC skiing could differ between race formats. For example, sprint skiers have different physiological characteristics, with higher muscle mass and anaerobic power, than performance-matched distance skiers who are able to produce a higher aerobic power (Losnegard and Hallén, 2014). However, the most common race format in XC skiing, the mass-start events, are virtually unexplored (Losnegard, 2019), and the impact of physiological and biomechanical performance-determining variables for mass-start performance is currently unknown.

Mass-start competitions are performed on the same race-tracks as time trials. However, since many skiers are racing together, the tactical elements will play a greater role for the result and could also influence the physiological and biomechanical demands. Mass-starts are commonly decided by a mass sprint or by a sprint between a few remaining contestants, and more seldom by a single skier crossing the finish solo after a breakaway. In all cases, high capacity to produce aerobic and anerobic power, together with high efficiency in the most important sub-techniques, should enable skiers to work at a lower relative intensity to follow the pace, and thereby reduce the accumulation of fatigue before entering the final sprint.

The extent to which physiological and biomechanical variables determine the different components and the overall performance in mass-start XC skiing competitions may be valuable information to further optimize training and competition strategies. To explore factors important for XC skiing mass-starts, the main purpose of this study was to investigate physiological and biomechanical determinants of sprint ability following variable intensity exercise when roller ski skating.

MATERIALS AND METHODS

Overall Design

In this study, we measured physiological and biomechanical variables in elite skiers performing a simulated mass-start [i.e., variable intensity exercise followed by an all-out sprint (AOS)], while roller ski skating on a treadmill. The track was organized as seven identical 3-min laps consisting of four different segments simulating a moderate uphill (S1), a flat segment (S2), a steep uphill (S3), and a simulated downhill (S4; **Figure 1**). The profile of the track was designed according to standards of the International Ski Federation, where the following sub-techniques could naturally be utilized (Andersson et al., 2010): gear 2 (G2), a technique for skiing uphill that involves an asymmetrical double pole push in connection with every other leg push; gear 3 (G3), a technique used on moderate inclines and level terrain that involves one double pole push together with every leg push; gear 4 (G4), a symmetrical double pole push in connection with every other leg push, used on level terrain; and gear 7 (G7), when the skier is in a downhill deep stance position without moving poles or legs. Although the track was designed for the use of specific sub-techniques in each segment, the skiers could freely select sub-techniques themselves.

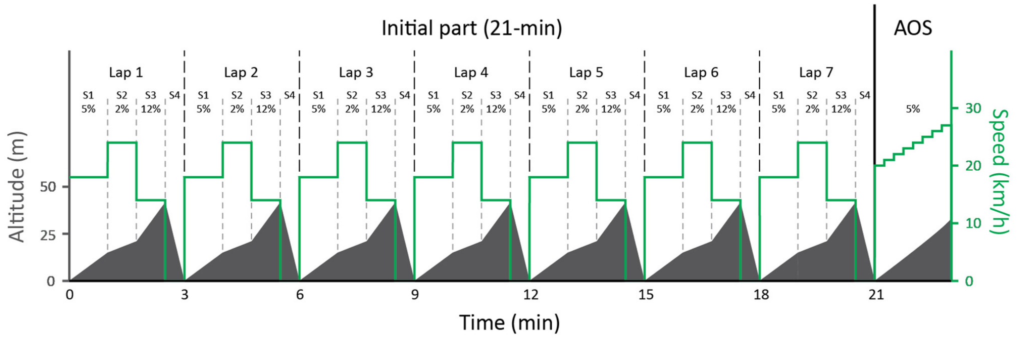

FIGURE 1 | Protocol showing the changes in altitude and speed for the simulated mass-start competition divided into a 21-min initial part with seven 3-min laps where each contains 4 segments (S), followed by an all-out incremental sprint (AOS) with gradually increased speed each 15 s until exhaustion. Although the track was designed for the use of specific sub-techniques in each segment, the skiers could freely select sub-techniques themselves during the entire test.

The protocol consisted of two consecutive parts with the same preset load for all skiers: (1) a low-intensity familiarization during a 21-min bout on the simulated competition track and (2) the simulated mass-start competition, where the initial 21-min part on the simulated competition track was performed at high intensity and immediately followed by an AOS, with gradually increasing speed until exhaustion. The initial 21-min part was projected to simulate the "stay-in-the-group" condition of a mass-start, while the AOS was designed to assess the residual physiological capacities required to perform well during the final part of a mass-start race. Oxygen uptake (VO_2), heart rate (HR), near infrared spectrometry (NIRS), kinematics and pole forces were monitored continuously, while blood lactate concentration (BLa), and rating of perceived exertion (RPE) were measured directly after each part. In addition, performance-determining variables [gross efficiency (GE) and VO_{2Max}] were measured on a separate day.

Participants

Thirteen elite male Norwegian skiers, consisting of eight XC skiers (distance FIS points: 47 ± 21) and five biathletes, participated in the study (**Table 1**). All skiers were healthy and free of injuries at the time of testing. The skiers were instructed to prepare in the same manner as before a competition, but with no strenuous exercise the last 24 h before the test. All skiers were conversant with treadmill roller skiing and VO_2 measurements from previous testing sessions and daily training routines.

Equipment

Laboratory and Ski Equipment

The protocol was performed on a 3-by-5-m motor-driven treadmill on roller ski (Forcelink S-mill, Motekforce Link, Amsterdam, Netherlands). The skiers used poles of their individually chosen lengths with special carbide tips. All skiers wore their own skating XC shoes but used the same pair of skate elite roller skis (IDT Sports, Lena, Norway) with an NNN binding system (Rottefella, Klokkarstua, Norway) and with standard category 2 wheels to minimize variations in roller resistance. The rolling friction coefficient (μ) was tested before, at various times during, and after the study using the towing test described by Sandbakk et al. (2010), providing an average μ-value of 0.016.

The visual movement of the skiers were captured from behind with a video camera (GoPro Hero6, Inc, San Mateo, CA, United States). The skiers wore a safety harness connected to an automatic emergency brake at the high intensity parts of the tests. Incline and speed of the treadmill were calibrated before and after the study by using the Qualisys Pro Reflex system and Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden).

Physiological Measurements

Before testing, the body mass of each skier was determined with an electronic body-mass scale (Seca model nr:877; Seca GmbH & Co. KG., Hamburg, Germany). Respiratory variables were measured continuously using open-circuit indirect calorimetry (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany). Expired gas was passed through a mixing chamber and analyzed

TABLE 1 | Anthropometric, physiological, and performance characteristics [mean value ± standard deviation (SD)] of the thirteen male skiers participating in the study.

Variables	Mean value	*SD*
Age (years)	24.8	*2.7*
Body height (cm)	184	*6.0*
Body mass (kg)	79.3	*5.2*
Body mass index ($kg \cdot m^{-2}$)	23.4	*1.0*
VO_{2Max} ($mL \cdot min^{-1} \cdot kg^{-1}$)	69.5	*3.6*
VO_{2Max} ($mL \cdot min^{-1}$)	5505	*364*
HR_{Max} ($beat \cdot min^{-1}$)	193.5	*7.0*
Skinfold thickness triceps brachii arm (mm)	6.6	*1.8*
Skinfold thickness vastus lateralis leg (mm)	7.3	*1.3*

HR_{Max}: The highest measured heart rate ($beat \cdot min^{-1}$). VO_{2Max}: The highest 30-s moving average (based on 10-s mixing chamber values) during the incremental maximum test in the pretest.

continuously. The instruments were calibrated against ambient air and a commercial gas with known concentrations of O_2 (15%) and CO_2 (5.85%) before the start of each test. The flow transducer (TripleV, Erich Jaeger GmbH, Hoechberg, Germany) was calibrated using a 3-L high-precision calibration syringe (5530 series, Hans Rudolph Inc., Kansas City, MO, United States). The data were collected as 10-s mixing chamber values and are given as body weight adjusted oxygen uptake (VO_2) and as percentage of VO_{2Max} ($\%VO_{2Max}$).

Garmin Forerunner 920XT (Garmin Ltd., Olathe, United States) was used to continuously measure HR at a sampling frequency of 1 Hz. Relative HR ($\%HR_{Max}$) was calculated as % of maximal HR (HR_{Max}) for each skier, and HR_{Max} was defined as the highest measured value for each person measured at any time during the tests. BLa was measured using Biosen C-line Sport lactate measurement system (EKF Industrial Electronics, Magdeburg, Germany) collecting 20 μL blood form the fingertip. The device was calibrated every 60 min with a 12-mmol μL standard concentration. RPE for upper body, lower body and overall were recorded using the 6–20-point Borg Scale (Borg, 1982).

NIRS Measurements

Muscle oxygenation was assessed using a wireless NIRS system (Portamon, Artinis Medical Systems, Netherlands) consisting of two optodes, each with three transmitters and one receiver. All transmitters emitted light at wavelengths of 760 and 850 nm and used a sample rate of 10 Hz. The optode sites were shaved before placement. The two optodes were placed on the vastus lateralis of the right leg and the long head of the triceps brachii on the right arm and secured with tape and elastic bandages before they were covered with a black cloth to prevent the interference of ambient light. At the end of the test, skinfold thickness was measured (three times) at the sites of optode placement using a skinfold caliper (Holtain skinfold caliper, Holtain Ltd, Crymych, United Kingdom), see **Table 1**. The data from the different NIRS sensors was collected and synchronized in time by the designated software and the tissue saturation index (TSI) with a Fit factor higher than 99.8% was used in the study. In order to remove the resulting 1-s gaps in the NIRS-data, it was chosen to interpolate with the average value of the two neighbor points. Here TSI_{leg} is TSI from the sensor placed on vastus lateralis of the right leg, and TSI_{arm} is TSI from the sensor placed on the long head of the triceps brachii on the right arm.

Movement and Pole Force Data

Eight Oqus 400 infrared cameras captured 3D position of passive reflective markers placed bilaterally on the body, on roller skis and poles with a sampling frequency of 200 Hz. The specific body locations of the reflective markers were on the ski boot at the distal end of the fifth metacarpal, the lateral malleolus (ankle), lateral epicondyle (knee), greater trochanter (hip), lateral end of the acromion process (shoulder), lateral epicondyle of humerus (elbow), and styloid process of ulna (wrist). One marker was placed on the lateral side of each pole, ~5 cm below the handle, and one marker was placed on the lateral side of the pole tips, for calculation of pole direction and thus direction of pole forces. For ski measurements one marker was placed 1 cm behind the front wheel, and one marker 1 cm in front of the back wheel of each roller ski. The motion capture system only measured every second lap (lap 1, 3, 5, and 7) during the simulated mass-start, to reduce risk for overload of data and system failure.

Instrumented ski pole grips (Proskida, Whitehorse, YT, Canada) were used to measure the axial (resultant) force directed along the poles. The data was streamed to a mobile phone via the Bluetooth protocol, and later downloaded to a computer and synchronized with the movement data. The sampling frequency of the force data was 100 Hz.

An IMU placed on the front of the chest (Physiolog 5 from GaitUp SA, Lausanne, Switzerland) was used to provide continuous motion data for automatic detection and classification of the skating sub-techniques and the corresponding movement pattern. The IMU consisted of a 3D-accelerometer and 3D-gyroscope with sampling frequency 256 Hz in addition to a barometric pressure sensor with sampling frequency 64 Hz. Data was stored locally on the sensor during the test and later downloaded to a computer.

Protocol

The preparation consisted of attaching the wearable sensors to the body, then the skiers sat passively for 5 min to create a data basis for the NIRS measurements before standing still on the treadmill for 4 min to get a baseline for the respiratory measurements. The active protocol started with a short calibration procedure for the IMU sensor before the 18-min warm up was performed at low to moderate intensity [5 min of G3 at 10 $km \cdot h^{-1}$and 5% incline before two 4-min stages using G2 and G4 (10 $km \cdot h^{-1}$ at 8% incline)] as part of the NIRS calibration.

The 21-min low-intensity familiarization in the competition track was performed on the treadmill following the pre-set terrain profile (see **Figure 1**) and set speeds (S1:14 km/h, S2: 20 km/h, and S3: 8 km/h). Thereafter, a 5-min recovery period was given before the initial 21-min part of the simulated mass-start protocol, simulating the "stay-in-the-group" condition, was performed on the same inclines, but at higher speeds (S1:18 km/h, S2: 24 km/h, and S3: 14 km/h). The bout was immediately followed by an incremental AOS to determine sprint abilities required during the final part of a mass-start race. The AOS was performed at 5% incline starting at 20 $km \cdot h^{-1}$ and with a 1 $km \cdot h^{-1}$ increase in speed every 15 s (see **Figure 1**). Each skier could freely choose sub-technique and received continuous visual and verbal feedback concerning the upcoming terrain and the time till the next segment but was blinded to the performance of the other skiers.

Based on pilot testing and on performance level of the participants, speeds were chosen so that some skiers (the less good ones) would likely not manage to complete the whole 21-min protocol (simulating that the skiers were not able to "stay-in-the-group"), while some skiers (the best ones) would be well able to complete it. Accordingly, at any time during the mass-start competition, skiers could take an unlimited number of 30-s breaks (by grabbing the rope at the front of the treadmill, simulating tuck). The protocol would keep running regardless, and so the skier would continue skiing wherever after each such 30-s break. The skiers were clearly instructed about this opportunity before the start and explained that such a break would simulate a real-life competition situation in which they felt they could no longer keep up with the front, and after a 30-s break they would be skiing together with another group of trailing skiers. They were blinded to the results by the other skiers and were told to still aim for a best possible time in the AOS and thereby achieving the highest rank possible in the mass-start. The overall performance ranking used in the statistics was determined from time-to-exhaustion during the AOS in addition to the number of breaks, where all those finishing the initial 21-min protocol without breaks were ranked before those requiring one, two or three breaks, respectively.

Protocol for Measuring Performance-Determining Variables

To obtain performance-determining variables while roller ski skating (e.g., VO_{2Max} and GE), additional laboratory measurements were conducted on a separate day within 1 week prior to the simulated mass-start. This protocol consisted of a 5-min standardized low-intensity warm-up on the treadmill before each skier performed a total of twelve 4-min bouts with set speed/incline at four different intensity levels, starting with the lowest level. For every intensity level, the three different bouts with specified skiing techniques were performed in randomized order (G2: 12% incline at 6/7/8/9 $km \cdot h^{-1}$, G3: 5% incline at 10/12/14/16 $km \cdot h^{-1}$, and G4: 2% incline at 15/18/21/24 $km \cdot h^{-1}$), and approximately 2 min recovery was given between each stage. The corresponding speeds for each technique were chosen to obtain similar RPE and BLa across sub-techniques for each intensity level. The inclines employed represent typical inclines where these techniques are employed by elite skiers and were based on previous research (Pellegrini et al., 2013; Stöggl and Holmberg, 2016). After the last submaximal exercise bout, a 15 min recovery period (rest and easy warm up) was followed by a maximal incremental test. The starting incline and speed were 10.5% and 11 $km \cdot h^{-1}$, after which the speed was kept constant, while the incline was subsequently increased by 1.5% every minute until 14.0%. Thereafter, the speed was increased by 1 $km \cdot h^{-1}$ every minute until exhaustion. VO_2 was monitored continuously and the highest 30-s moving average (based on 10 s mixing chamber values) was defined as VO_{2Max}.

The submaximal data from this protocol was used to calculate GE as the external work rate divided by the metabolic rate, in accordance with Sandbakk et al. (2010). The metabolic rate was calculated from the average VO_2 of the last min of each submaximal exercise bout and the oxygen equivalent, using the associated average respiratory exchange ratio and standard conversion tables (Massicotte et al., 1996). The work rate was calculated as the sum of power against gravity [$Pg = m \cdot g \cdot \sin(\alpha) \cdot v$] and friction [$Pf = m \cdot g \cdot \cos(\alpha) \cdot \mu \cdot v$]; where m is the mass of the skier, g the gravitational acceleration 9.81 m/s^2, α the angle of treadmill incline, v the treadmill speed and μ the frictional coefficient. In this paper the average GE was calculated (based on 11 or 12 submaximal exercise bouts; one subject did not complete the G2 exercise bout at the highest intensity, because of a BLa above 4 $mmol \cdot L^{-1}$ at the previous intensity) and used in addition to mean values of each sub-technique, i.e., G2, G3, and G4.

Data Analysis

Cycle Detection and Classification of Sub-Techniques

The accelerometer data from the IMU (placed on the chest) was used to automatically detect and classify each individual cycle into a sub-technique using Gaussian filtering and a trained support vector machine learning model with a similar method as used in Rindal et al. (2018). Subsequently, the data was manually examined and corrected for errors in classification by comparing the classified cycles with the video and the graphic representation of filtered accelerometer signals. The accuracy of the model on these data was above 99%. The cycle detection was based on the sidewise movement of the upper body, with cycle start defined at the point when the upper body is in a left position and with the lowest acceleration. Cycle detection together with the treadmill speed were used to derive CL and CR of each cycle. The cycles were classified into the sub-techniques G2, G3, G4, or Other, where Other included G5, transitions between sub-techniques, simulated downhill (G7) and not-skiing activities. The algorithms for cycle detection, model development and classification of sub-techniques were implemented in Matlab R2018b from MathWorks.

Calculation of Power-Distribution Between Poling and Ski Push-Offs

The marker position data and pole force data were low pass filtered (8th order Butterworth, 15 Hz cut-off) before further procession. Force and kinematics were synchronized offline (in MATLAB) for each lap recorded by detecting the first instance of pole touch down on the treadmill belt. This touchdown was defined as the first instant when the pole force reached 10 N. The body center of mass (CoM) was calculated based on the position data and body segments mass properties according to de Leva (1996). CoM velocity was obtained by numerical differentiation of position data. In skate style XC skiing, power is generated either by the poles or the skis. Instantaneous pole power (P_{Pole}) was calculated from pole force (F_{Pole}) and CoM velocity (V_{CoM}): [$P_{Pole} = F_{Pole\_x} \cdot V_{CoM\_x} + F_{pole\_y} \cdot V_{CoM\_y} + F_{Pole\_z} \cdot V_{CoM\_z}$] with x, y, and z representing components of F_{Pole} and V_{CoM} in the forward-backward (x), sideways (y), and vertical (z) directions (Donelan et al., 2002). P_{Pole} was calculated independently for each pole first, and then summed. The difference between work rate (P_{Cycle}) and cycle average P_{Pole} was interpreted as average ski power (P_{Ski}). Relative P_{Pole} ($\%P_{Pole}$) and relative P_{Ski} ($\%P_{Ski}$) was calculated as % of P_{Cycle} for each skier, and relative $P_{PoleLeft}/P_{PoleRigth}$ ($\%P_{PoleLeft}/\%P_{PoleRight}$) was calculated as % of P_{Pole} for each skier. Two of the skiers had missing power data for the whole test due to technical issues and are therefore not included in the power calculations.

Synchronization of Data and Definitions

All sensor data (HR, VO_2, TSI_{Leg}, TSI_{Arm}, CL, CR, sub-technique, P_{Cycle}, $\%P_{Pole}$, $\%P_{Ski}$, $\%P_{PoleLeft}$, and $\%P_{PoleRight}$) were synchronized in time to a common master timeline and compound into one dataset with 1 Hz resolution before the means were calculated. Time offsets from the master timeline for treadmill speed and incline, HR, VO_2, and NIRS data were manually recorded during the data collection. Time offsets for IMU-derived data (CL, CR, and sub-technique) were found based on identifying three synchronization jumps in the IMU data and on video. Reduction to 1-Hz resolution was done by calculating the mean for each second of data, which was the case for all types of data except the NIRS data where the mean 1-Hz values were calculated over three seconds to remove 1-s gaps resulting from the abovementioned filtering.

When comparing mean values for the skiers according to performance, the period from lap 1 to lap 3 in the mass-start were used instead of all laps, to be able to include all skiers. This was also the case when comparing mean values for the mass-start AOS, here only the first three steps were used. When comparing use of sub-techniques in **Figure 3**, the skiers were divided into two groups according to their performance-ranking, group 1 consisted of the nine skiers that completed the protocol as planned, and group 2 consisted of the remaining four skiers that needed one or more 30-s breaks due to exhaustion. Difference between segments and drift for physiological values (VO_2, HR, and TSI) were calculated only for group 1 due to the (slightly) different load for group 2 in the last 4 laps, while drift in kinetic and kinematic variables (power, CL, and CR) were calculated for all skiers since this was linked to a specific sub-technique and thereby the breaks were automatically excluded (classified as Other). For the same reason **Figure 2** shows only data for group 1, while **Figure 4** shows data for all skiers.

Statistical Analysis

All variables are presented as mean values for each skier in **Tables 2**, **3**. Before calculating lap-to-lap drift and differences between segments, all data were tested for normality using a Shapiro–Wilk test in combination with visual inspection of data. One-way ANOVA with Tukey's HSD *post hoc* test was used for analyzing differences in the measured physiological variables between the segments, with the first lap being excluded from the analysis. A paired sample t-test was used to examine lap-to-lap drift, with drift in physiological variables being defined as the difference in mean values of lap 7 min lap 2 (to compensate for the delayed kinetic response on lap 1 due to starting from rest). Drift in kinetic and kinematic variables (power, CL, and CR) was defined and calculated as the difference in mean values of lap 7 min lap 1.

Correlations between performance ranking [determined from time to exhaustion (TTE) in the AOS, with those requiring one or more breaks during the mass-start being placed behind those with less breaks, independent of TTE] and the different variables, were calculated using the Spearman's product-moment correlation coefficient. In addition, Pearson's correlation coefficient between TTE and the different variables for the 9 skiers that completed the entire protocol without breaks (group 1) was calculated. The interpretation of the magnitude of linear association between the variables were evaluated according to Hopkins et al. (2009) as trivial: $r < 0.1$, small: $0.1 \leq r < 0.3$, moderate: $0.3 \leq r < 0.5$, large: $0.50 \leq r < 0.7$, very large: $0.7 \leq r < 0.9$, and extremely large: $0.9 \leq r < 1$. The level of statistical significance was set at $\alpha = 0.05$, and $0.05 < \alpha < 0.10$ was regarded as trends. All statistical analyses were performed using IBM SPSS Software Version 26.0 (SPSS Inc., Chicago, IL, United States).

RESULTS

Individual mean values for physiological capacities from the simulated mass-start and performance determining variables are provided in **Table 2** and kinematic variables and power distributions are provided in **Table 3**. The dynamics of the physiological variables during the simulated mass-start for the nine skiers that completed the entire protocol without breaks (group 1) are displayed in **Figure 2**, the skiers that needed breaks in order to complete (group 2) are not included due to a different load. Mean values of each sub-technique as a function of lap number for both groups are being shown in **Figure 3**, and CL, CR and power distribution as a function of lap number and sub-technique for each segment for all skiers are given in **Figure 4**.

All physiological variables fluctuated according to simulated terrain, although a delay in the physiological measured response was present (**Figure 2**). $\%HR_{Max}$ in the moderate uphill (S1) was significantly lower than $\%HR_{Max}$ in the preceding downhill segment [-4.1 ± 1.4 percentage points (pp), $p = 0.02$] and the steep uphill (S3; -5.4 ± 1.4 pp, $p = 0.002$), while it did not differ significantly from $\%HR_{Max}$ in the flat segment (S2). $\%VO_{2Max}$ in the moderate uphill (S1) was significant lower than $\%VO_{2Max}$ in all other segments, with it being 8.0 ± 2.0 pp lower than during the preceding downhill (S4; $p < 0.001$), -14.3 ± 2.0 pp lower than during the flat segment (S2; $p < 0.001$) and -12.1 ± 2.0 pp lower than during the steep uphill (S3; $p = 0.001$). In addition, TSI_{Leg} and TSI_{Arm} also fluctuated according to the specified terrain segments (**Figure 2**), but there were no significant differences between the mean values for the different segments. There was a significant lap-to-lap drift in HR (7.9 pp, $p < 0.001$), in TSI_{Arm} (-3.0 pp, $p = 0.007$) and in power distribution between poling and ski push off's (-7.7 pp, $p = 0.006$). However, no significant drift in TSI_{Leg}, VO_2, CL, or CR was present.

An overview of significant correlations between variables measured during the simulated mass-start and the performance-determining variables are presented in **Table 4** and **Figures 5**, **6**. Here, $\%HR_{Max}$ and $\%VO_{2Max}$ during the simulated mass-start showed large- to extremely large correlations with performance, while the body-mass normalized VO_2 and VO_{2Max} (**Figure 6**) displayed large correlations with performance. Accordingly, the ability to increase HR and VO_2 in the AOS, beyond the corresponding values achieved during the initial 21-min, showed very large correlation with mass-start performance (**Figure 5**). In addition, RPE during the mass-start showed a very large correlation and BLa measured directly after the AOS a large correlation with performance. Sub-technique selection (distribution of G2 vs G3) during the main part of the mass-start showed a large correlation with performance, with the best-performing skiers using more G3 (**Figure 3**). Average GE and specific GE in G2 and G3 had very large correlation with performance, while

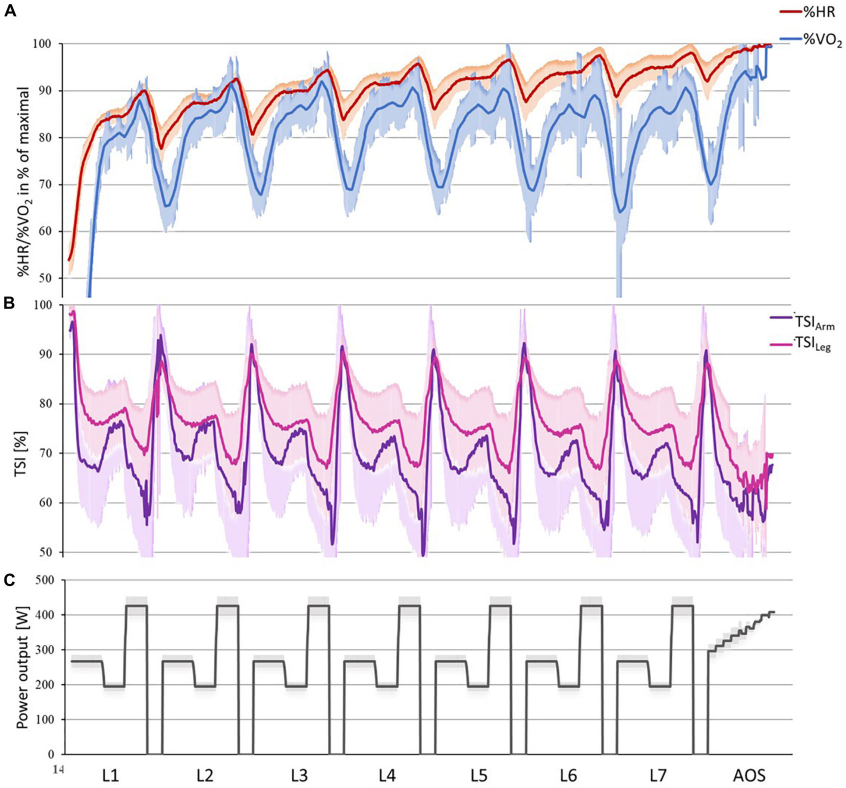

FIGURE 2 | Mean values and standard deviation with 1-Hz resolution for **(A)** heart rate (HR) and oxygen uptake (VO_2; 30-s moving average) and **(B)** tissue saturation index for the vastus lateralis of the right leg (TSILeg) and the long head of the triceps brachii on the right arm (TSIArm), and **(C)** power output in the simulated mass-start for the 9 skiers who were able to finish the entire protocol without requiring breaks. The data for the 4 skiers who needed breaks followed the same pattern.

GE obtained using G4 correlated only moderately with performance. A longer CL and a lower CR in G3 during the AOS was largely correlated with performance. There was considerable subject-to-subject variation in power distribution from poles and skis, and between power produced by the left and right pole, but no significant correlations to performance (**Figure 4**).

DISCUSSION

The primary purpose of this study was to investigate the physiological and biomechanical determinants of sprint ability following variable intensity exercise when roller ski skating. As expected, the physiological and biomechanical responses fluctuated in response to the changes in terrain during the simulated 21-min mass-start. Directly following this approach, the performance of skiers was ranked by TTE on the AOS. Here, better performance rank was associated with higher VO_{2Max} and GE as well as the ability to ski on a lower relative intensity (i.e., $\%HR_{Max}$, $\%VO_{2Max}$, and RPE) during the initial 21-min of the simulated mass-start. In addition, the potential to increase HR and VO_2 in the AOS, beyond the corresponding values achieved during the initial 21-min of the simulated mass-start, correlated with performance. Finally, greater utilization of the G3 sub-technique in the steepest uphill, as well as a trend for longer CL during the AOS, were associated with better performance.

In this first study exploring physiological and biomechanical performance-determining variables in an experiment aiming to simulate the mass-start event in XC skiing, we observed increased VO_2 and HR values from the uphills and reduced values from the downhills and flat terrain during the initial 21-min, as previously described in time trials and during high-intensity training in varying terrain (Bolger et al., 2015; Solli et al., 2018; Haugnes et al., 2019a). However, both HR and VO_2 had a delay in the response to the changing workload as also shown previously (Gløersen et al., 2018, 2020), which is probably due to the combination of a real delayed physiological response (Barstow

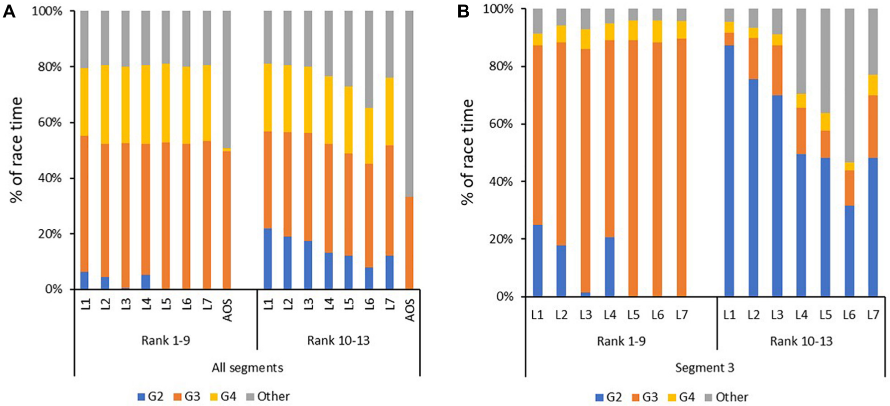

FIGURE 3 | Distribution of sub-techniques [in % of time] for each of the seven 3-min laps (L) during the simulated mass-start, with the skiers divided into two groups: **(A)** for all four segments in the initial 21-min and the all-out sprint (AOS; see **Figure 1** for the protocol) and **(B)** for the steepest uphill. Skiers ranked 1–9 are those who were able to finish the entire protocol without requiring breaks and rank 10–13 consists of the 4 lowest ranked skiers that required one or more breaks to complete protocol.

and Molé, 1991) in addition to measurement delays (e.g., low resolution of VO_2 data and a delay due to data processing and averaging in the HR monitor). While the mean lap values for HR had a significant lap-to-lap drift, the mean VO_2-values for each lap remained stable throughout the entire 21-min. However, the large individual differences in the relative intensity (i.e., $\%\text{VO}_{2Max}$ and $\%\text{HR}_{Max}$), and thereby in the potential to increase HR and VO_2 in the AOS beyond the values achieved during the 21-min protocol, indicate that some skiers were working close to their maximum in the initial part of the mass-start. Accordingly, some skiers required one or more breaks, whereas others could perform the entire protocol quite comfortably.

In general, a similar picture is mirrored by the TSI values both for arms and legs, although the mean values for the different segments were not significantly different. The TSI_{Arm} and the distribution of power between poling and ski push offs had a significant lap-to-lap drift, with higher oxygenation saturation and more upper body effort in the first lap compared to the last lap. The shift in power distribution could have been done intentionally to save the legs toward the end, or possibly because the skiers got more fatigued in the upper than the lower body (i.e., reduced TSI_{Arm}) and therefore generated relatively more power from the legs. The latter finding is in line with two previous studies were elite skiers performed diagonal stride (Björklund et al., 2010) and double poling (Stöggl et al., 2013). These studies showed that O_2 extraction was lower and blood lactate production higher in the arms than the legs. This could indicate more fatigue in the arms relative to the legs and might be the reason why the skiers in our study used more relative power from the legs toward the end of the 21-min bout. In addition, this could also explain why the mean value for TSI_{Arm} was lower than for TSI_{Leg}, and why TSI_{Arm} had a small, but significant lap-to-lap drift. However, this lap-to-lap drift in power distribution did not influence CL and CR, both varied according to incline, speed and sub-technique utilization, but showed the same pattern within each sub-technique for all laps (i.e., no drift over time occurred).

The ability to perform well during the AOS at the end of the variable exercise during the simulated mass-start was largely correlated with both GE and VO_{2Max} (**Figure 6** and **Table 4**), which allowed better skiers to work on a lower relative intensity during the initial part of the simulated mass start. Accordingly, a large correlation between performance and measures of intensity during the simulated mass-start ($\%\text{HR}_{Max}$, $\%\text{VO}_{2Max}$, and RPE) was present (**Figure 5** and **Table 4**). This implies that a combination of higher aerobic energy delivery capacity and better efficiency allows the best performing skiers to start the AOS with less accumulation of fatigue and/or more anaerobic energy left. Both VO_{2Max} and GE have been shown to differentiate skiers on different performance levels and to allow skiers to utilize a higher aerobic power during time-trial competitions (Sandbakk and Holmberg, 2017). However, the novelty of this study is that these capacities seem to play a different role in mass-starts than shown for time-trials. Instead of using a superior VO_{2Max} and GE to increase speed, which is normally the case during time-trials, our findings imply that skiers who score high on these performance-determining variables can save energy and are therefore able to utilize their "reserves" better at the end of the race.

The best skiers were less fatigued after the 21-min initial part with variable intensity exercise with set speeds (i.e., simulating the conditions achieved in a mass-start race) and showed a better ability to increase VO_2 and HR with gradually increasing speed during the AOS. In contrast, the lower-performing skiers were not able to reach VO_2-values above those achieved during the steepest uphill in the main part of the mass-start, which may explain their limited ability to reach high speeds during the AOS. Specifically, the skiers ranked 6–13 in this study reached similar or higher HR and/or VO_2 values during the initial 21-min compared to the AOS, while the HR and VO_2

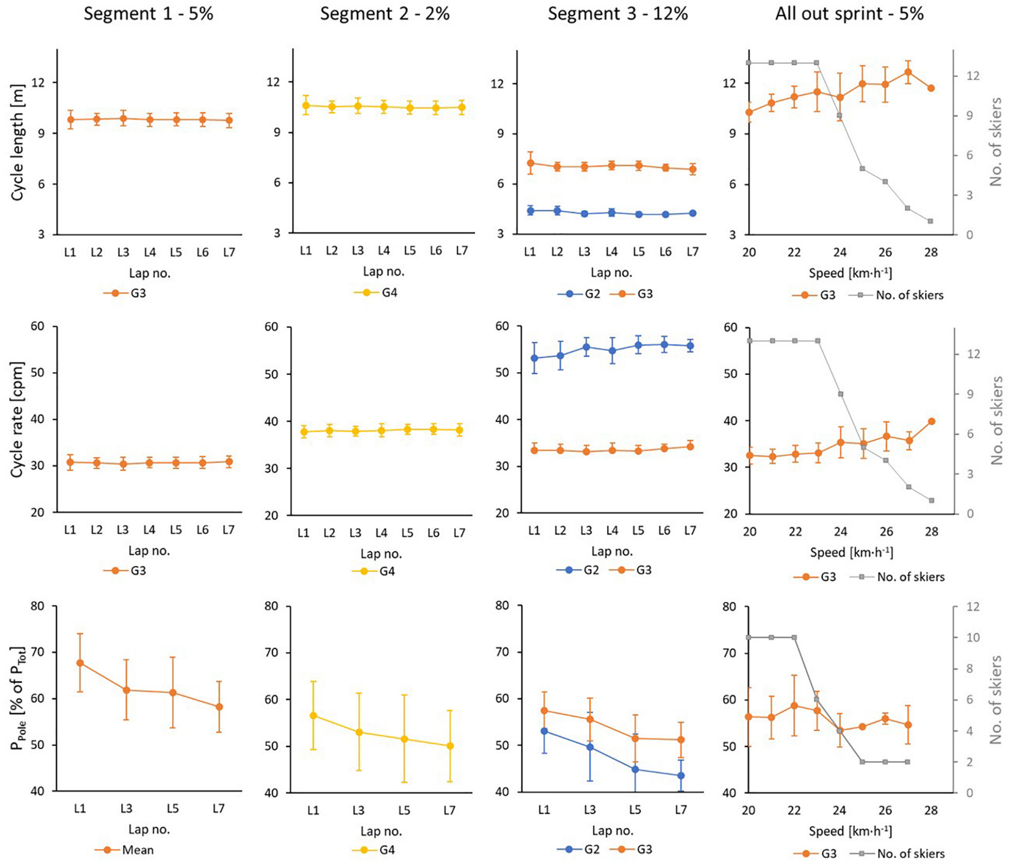

FIGURE 4 | Cycle length, cycle rate [in cycles per minute (cpm)] and body-mass normalized poling power (in %-age of mean cycle power) for the 13 skiers during a 21-min initial part with seven 3-min laps (L) where each contains 4 segments (with three of these analyzed here), followed by an all-out incremental sprint (AOS) with gradually increased speed each 15 s until exhaustion. In AOS the skiers are gradually stopping due to exhaustion, the number of remaining skiers is showed in gray color on the right axis.

values for the top ranked skiers were (much) higher during AOS. Although micro-pacing in XC skiing includes higher effort uphill and downregulation of effort in downhills (Gløersen et al., 2018; Karlsson et al., 2018; Stöggl et al., 2018b), it seems important for skiers to work below a certain threshold also in the steepest uphills, allowing them to recover sufficiently in the subsequent downhills. This is for example shown in a 15-km simulated time-trial race (Gløersen et al., 2020), where elite skiers repeatedly attained substantial oxygen deficits in uphill segments. However, the deficits for each segment in that study were relatively small compared to their maximal accumulated oxygen deficit (MAOD), and within a level that could rapidly be recovered. Still, the total accumulated race O_2 deficit was several times the MAOD, suggesting that this is an important energy contribution for an optimally paced race. Gløersen et al. (2020) argued that the ability to repeatedly use and recover the energy is an important performance indicator. In addition, a previous study comparing elite and lower-level skiers alternating between 3 min at 90% and 6 min at 70% of VO_{2Max} (Bjorklund et al., 2011) showed that lower-level skiers were less able to reduce BLa during the 70% intervals compared to elite skiers, even though there was no significant difference in BLa between the two groups after the first 90% interval (Bjorklund et al., 2011). These findings support the results presented here, illustrated by how the positive pacing strategies (involuntary) applied by the lower performing skiers in the initial 21-min limits their ability to recover and reach their full potential when sprinting at the end of the protocol.

In individual time-trial competitions, better-performing skiers utilize a more even pacing strategy than their lower-performing peers, who use a distinct positive pacing strategy and accumulate fatigue to a greater degree early in the race

TABLE 2 | Physiological responses measured during the simulated mass-start (MS) and performance-determining variables measured during a separate day for the 13 individual skiers involved in this study.

	Performance		MS – mean values (Lap 1 – Lap 3)					MS – after		MS – peak values				Performance determining variables				
Rank	30 s Breaks	TTE[s]	HR [% of HR_{Max}]	VO_2 [% of VO_{2Max}]	VO_2 [mmol·L^{-1}·kg^{-1}]	TSI $_{Arm}$ [%]	TSI $_{Leg}$ [%]	RPE [1–20]	Bla [mmol L^{-1}])	PeakHR [bpm]		$PeakVO_2$ [mL·min^{-1}·kg^{-1}]		VO_{2Max} [mL·min^{-1} ·kg^{-1}]	Gross efficiency [%]			
	#	AOS	IP	IP	IP	IP	IP	IP	AOS	IP	AOS	IP	AOS		G2	G3	G4	OA
1		130	83.5	74.2	54.7	59.4	61.3	16	10.5	182	193	70.5	74.3	73.8	17.7	15.9	12.7	15.4
2		119	85.1	73.2	53.4	43.8	51.9	17	7.2	184	190	71.7	73.4	73.0	17.4	15.1	12.6	15.0
3		101	87.3	78.2	53.2	45.2	55.3	16	14.3	171	177	69.4	71.0	68.1	17.0	14.9	12.0	14.7
4		91	90.2	74.9	55.0	45.0	58.1	18	12.0	199	202	73.1	71.7	73.4	17.3	15.4	13.0	15.2
5		82	88.0	73.2	53.0	58.5	64.6	15	8.7	187	189	67.6	67.7	72.5	16.9	14.8	12.9	14.9
6		74	88.8	76.7	56.8	36.0	51.4	17	12.9	203	202	72.7	71.4	74.0	16.4	14.5	12.1	14.4
7		65	88.5	79.3	51.3	47.8	57.3	20	10.2	191	189	66.1	61.8	64.8	17.4	14.9	12.8	15.0
8		60	90.6	78.0	53.4	50.1	63.3	19	12.0	193	194	66.1	65.0	68.5	17.3	15.0	12.9	15.1
9		47	89.0	79.4	53.2	65.3	69.7	17	11.8	193	189	68.6	62.9	67.0	17.1	15.1	12.7	15.0
10	1	50	93.7	81.6	58.8	54.4	65.2	20	16.7	202	200	72.6	69.1	72.0	15.8	14.0	11.7	13.8
11	2	62	92.6	83.8	54.7	42.4	46.5	19	18.7	195	196	69.3	63.3	65.3	16.7	14.6	12.1	14.3
12	2	47	91.5	86.6	55.2	63.8	55.6	19	15.1	201	196	67.3	61.1	63.8	16.5	14.5	12.0	14.4
13	3	66	91.1	82.9	56.2	51.0	54.1	20	12.0	189	190	70.9	70.6	67.8	16.2	14.0	12.1	14.1

Values collected during the simulated mass-start are shown either for the initial part (IP) or after the all-out sprint (AOS). Rank, ranking in the simulated mass-start; TTE, time to exhaustion; HR, heart rate; HR_{Max}, the highest measured heart rate; VO_2, oxygen uptake; VO_{2Max}, The highest 30-s moving average (based on 10 s mixing chamber values) during the incremental maximum test; TSI_{Leg}, tissue saturation index for the vastus lateralis of the right leg; TSI_{Arm}, tissue saturation index for the long head of the triceps brachii on the right arm; RPE, rate of perceived exhaustion; BLa, blood lactate concentration; and Peak HR/VO_2, the highest measured HR/VO_2 during the specified bout.

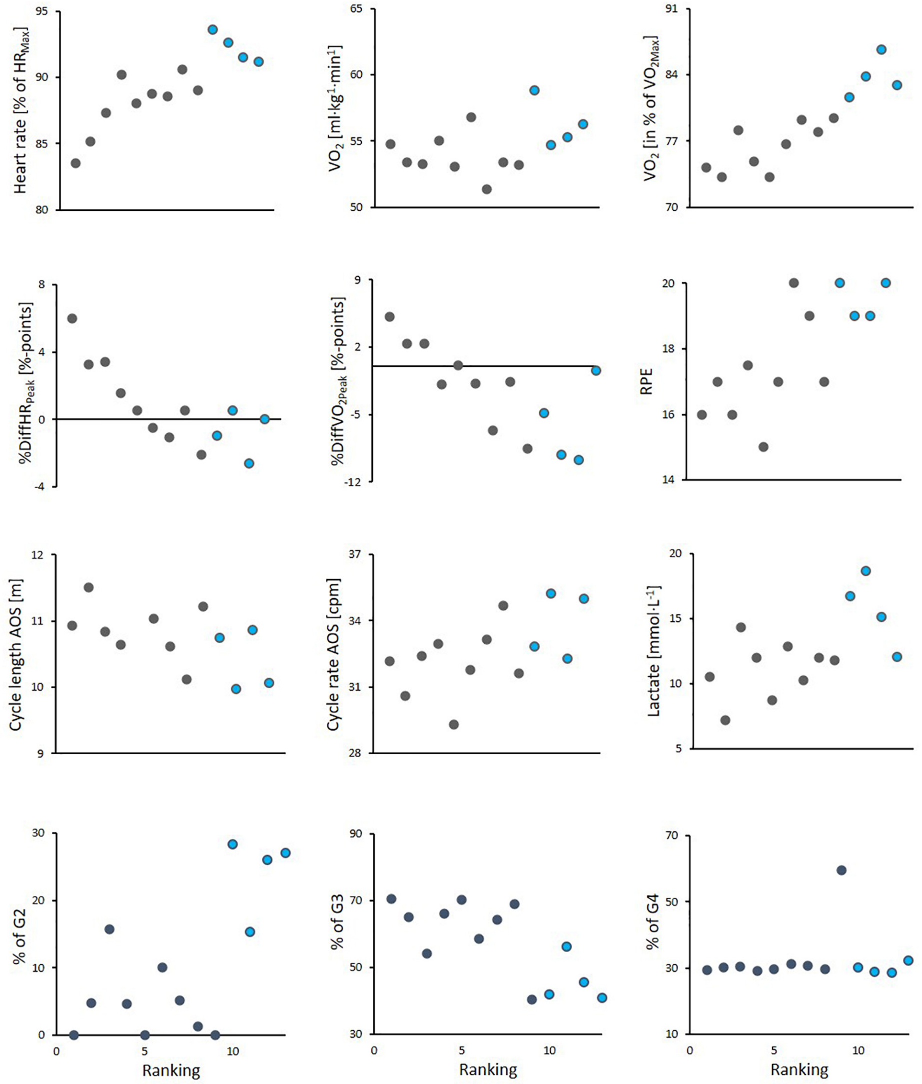

FIGURE 5 | Scatter plots for athlete ranking in the simulated mass-start with the following parameters: mean values of heart rate (HR), oxygen uptake (VO$_2$) and sub-technique selection during the first three laps of the simulated mass-start, as well as to the rate of perceived exhaustion (RPE) for the initial 21-min of the mass-start, cycle length and cycle rate during the first 3 steps of the incremental all-out sprint (AOS), blood lactate concentration (BLa) measured directly after the simulated mass-start and the difference between peak values of relative heart rate (%HR$_{Max}$) and oxygen uptake (%VO$_{2Max}$) in the main part of the mass-start and the corresponding values during the AOS (%DiffHR$_{Peak}$/%DiffVO$_{2Peak}$). The 9 skiers completing the entire protocol without breaks are shown with black color, while the 4 skiers who needed breaks are shown in blue color.

(Losnegard et al., 2016; Stöggl et al., 2018a, 2020). Our present results show that the forced pacing applied by the lower performing skiers in the simulated mass-start, which was too positive, forced them to accumulate fatigue in the initial part of the mass-start, which might have limited their ability to reach their full aerobic potential in the AOS. This novel finding provides important information about the effect of pacing on energetic capacity, with relevance both to mass-start events in XC skiing and other endurance sports.

Sub-technique selection in the steepest uphill, which had the highest workload, resulted in a very large Spearman's correlation with performance, where the best skiers used more G3 at the expense of G2. This finding is in line with conclusions from two recent reviews (Stöggl et al., 2018a; Zoppirolli et al., 2020), where performance was linked to the ability to maintain speed in a specific section of a race. In our study, the skiers used the same speed in all similar terrain sections, but in line with the differences in relative intensity during the mass-start, also sub-technique selection was clearly differentiating performance levels. Specifically, the sub-technique selection in the steepest uphill divided the skiers in two groups, were only the best skiers utilized G3. In contrast, the 3 skiers who only used G2 in this section were in the group of lower-performing skiers requiring one or more breaks. This is further exemplified when correlating the 9 skiers performing the entire protocol using Pearson's correlation, in which the significance between sub-technique selection and performance disappeared.

Coinciding with less tiredness and better aerobic power during the AOS, better performing skiers also showed the ability to concurrently produce longer CL and thereby have a lower CR at the set speed than their lower-performing peers. Two recent reviews define CL to be a trustable significant performance indicator, while CR is to a lower degree associated with performance (Stöggl et al., 2018a; Zoppirolli et al., 2020). However, none of the previous studies have examined temporal patterns in a finish-sprint where skiers had various degrees of accumulated fatigue as often occurring during a mass-start race. It should, however, be noted that these correlations were not significant when correlating the 9 skiers performing the entire protocol.

Relative power distribution between poles and skies, and between the power from left and right pole, displayed large variation between skiers for all sub-techniques, but we found only small, non-significant correlations with performance. This is in contrast to the conclusions from the meta-analysis by Zoppirolli et al. (2020), where more equal power distribution between sides was related to better performance. However, the large differences revealed in the use of sides and in the distribution of power from skis and poles may still be important information for each skier and can inform further technical development in training and competition. The same applies for oxygen saturation level in the muscles of arms and legs, where large individual differences occurred and only small to moderate correlations were found.

Strength and Limitations

The present study was performed indoors while roller ski skating on a treadmill, where both physiological and biomechanical variables can be measured more correctly and detailed than during a real mass-start race performed outdoors on snow. This approach induced both strengths and limitations, with the ecological validity being particularly limited compared to studies on snow where interactions between skiers, tactics and drafting would play main roles. Accordingly, this study aimed to examine specific components with high relevance for the mass-start race, such as the cost of skiing a given track with a set workload and the subsequent effect on the ability to sprint at the end of the race. In this context, our protocol excludes the variable draft from skiing in a group and other aspects related to group dynamics. While this aspect limits the ecological validity, our protocol assures that all skiers were performing at the same prescribed speed and

TABLE 3 | Distribution of sub-technique, power and cycle characteristics (mean values) measured during the initial part (IP; lap 1 to lap 3) of the simulated mass-start or during the first three steps of the all-out sprint (AOS).

	Sub-technique distribution				Power distribution					Cycle characteristics	
	G2 [%]	G3 [%]	G4 [%]	Other [%]	$\%P_{Cycle}$ [Watt]	$\%P_{Pole}$ [% of P_{Cycle}]	$\%P_{Ski}$ [% of P_{Cycle}]	$\%P_{PoleLeft}$ [% of P_{Cycle}]	$\%P_{Pole Rigth}$ [% of P_{Cycle}]	CL [m]	CR [cpm]
Rank	**IP**	**IP**	**IP**	**IP**	**IP**	**IP**	**IP**	**IP**	**IP**	**AOS**	**AOS**
1	0	55	23	22	283.3	60.9	39.1	48.3	51.6	10.9	32.2
2	4	53	24	19	292.5	52.1	47.9	43.9	56.1	11.5	30.6
3	12	42	24	22	ND	ND	ND	ND	ND	10.8	32.4
4	4	53	23	20	270.5	60.5	39.5	46.6	53.4	10.6	33.0
5	0	57	24	20	305.2	58.6	41.4	43.3	56.6	12.0	29.3
6	8	47	25	19	261.0	58.1	41.9	51.5	48.5	11.0	31.8
7	4	51	24	20	332.9	69.7	30.3	51.1	48.9	10.6	33.1
8	1	56	24	18	288.1	60.4	39.6	48.1	51.9	10.1	34.7
9	0	32	48	20	281.7	60.1	39.9	52.4	47.1	11.2	31.6
10	23	34	25	17	267.0	47.8	52.2	50.5	49.4	10.7	32.8
11	12	45	23	20	ND	ND	ND	ND	ND	10.0	35.2
12	21	36	23	21	286.3	59.8	40.2	44.8	55.2	10.9	32.3
13	22	33	26	19	300.2	50.7	49.3	46.6	53.4	10.1	35.0

Rank, ranking in the simulated mass-start; ND, no data; $\%P_{Cycle}$, mean cycle power; $\%P_{Ski}$, power from ski push offs in % of P_{Cycle}; $\%P_{Pole}$, power from poling in % of P_{Cycle}; $\%P_{PoleLeft}$, Power from left pole in % of P_{Pole}; $\%P_{PoleRigth}$, Power from right pole in % of P_{Pole}; CL, cycle length; and CR, cycle rate.

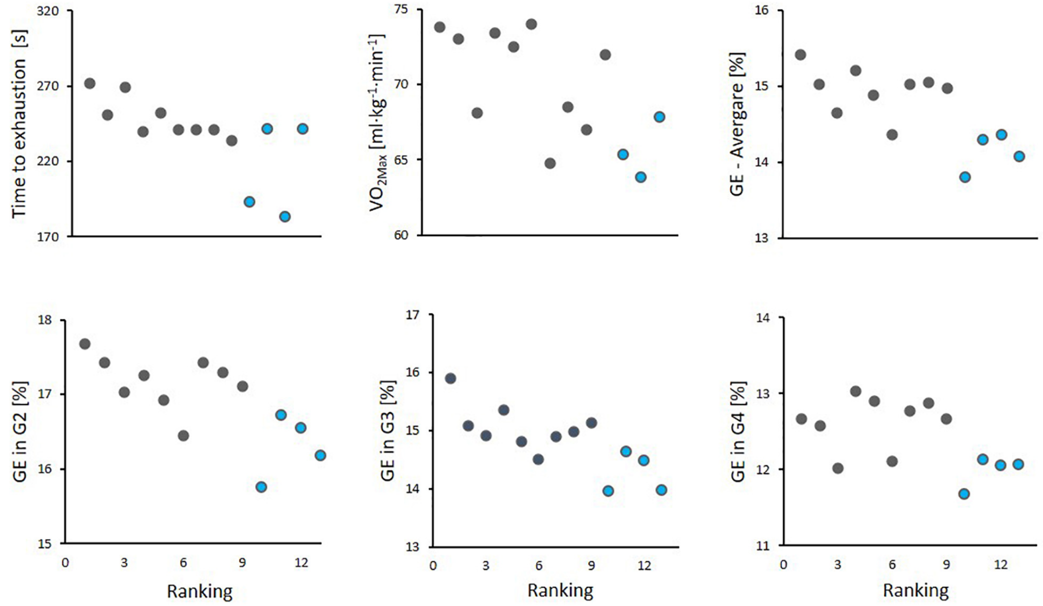

FIGURE 6 | Scatter plots for athlete ranking in the simulated mass-start with the following performance-determining variables: time to exhaustion in the maximal performance test, maximal oxygen uptake (VO_{2Max}) and gross efficiency (GE) (average for all sub-techniques (average), and for G2, G3 and G4 sub-techniques) for all 13 skiers. The 9 skiers completing the entire protocol without breaks are shown with black color, while the 4 skiers who needed breaks are shown in blue color.

TABLE 4 | Spearman's rank order correlation (R_S; for all 13 skiers) and Pearson's correlation (R_P; for the 9 skiers who completed the entire protocol without breaks) between ranking (Spearman's), respectively, time to exhaustion (Pearson's) in the simulated mass-start (MS) and variables measured during the MS in addition to performance determining physiological variables (PDV) measured on a separate day.

Correlation	Protocol	Parameter	Laps	R_S $N = 13$	P_S $N = 13$	Laps	R_P $N = 9$	P_P $N = 9$
Extremely Large: $R_S > 0.9$	MS – initial part	Peak HR [% of HRmax]	Lap 1–3	0.92	<0.001	All	*0.96*	*0.002*
Very large:	MS – initial part	Mean VO_2 [% of VO_{2Max}]	Lap 1–3	0.89	<0.001	All	*0.82*	*0.042*
R_S [0.70–0.89]	MS – initial part	Mean HR [% of HR_{Max}]	Lap 1–3	0.87	<0.001	All	*0.93*	*0.001*
	MS	%DiffHR_{Peak} (AOS – initial part) [pp]	All	−0.76	0.001	All	*−0.97*	*<0.001*
	MS – initial part	Rate of perceived exhaustion [1–20]	All	0.73	0.003	All	*0.69*	*0.192*
	PDV	Gross efficiency in G3	G3	0.72	0.006	G3	*0.74*	*0.126*
	MS	%DiffVO_{2Peak} (AOS-Initial part) [pp]	All	−0.72	0.001	All	*−0.94*	*0.001*
	MS – AOS	Peak VO_2 [$ml \cdot kg^{-1} \cdot min^{-1}$]	All	0.70	0.007	All	*0.88*	*0.016*
	PDV	Average gross efficiency	All	0.70	0.007	All	*0.57*	*0.576*
	PDV	Gross efficiency in G2	G2	0.70	0.008	G2	*0.65*	*0.265*
Large:	MS – initial part	Use of G3 [%]	Lap 1–3	0.69	0.009	L1–3	*0.68*	*0.207*
R_S [0.50–0.69]	PDV	VO_{2Max} [$ml \cdot kg^{-1} \cdot min^{-1}$]	Max	0.68	0.010	Max	*0.78*	*0.082*
	MS – AOS	Blood lactate [$mmol \cdot L^{-1}$]	After	−0.59	0.037	After	*−0.77*	*0.088*
	MS - initial part	Use of G2 [%]	Lap 1-3	−0.56	0.048	L1-3	*−0.39*	*0.703*
	MS – AOS	Cycle rate in G3 [cycles per minute]	3 steps	−0.52	0.071	3 steps	*−0.52*	*0.480*
	MS – AOS	Cycle length in G3 [m]	3 steps	0.52	0.071	3 steps	*0.52*	*0.480*

The MS is divided into the initial 21-min part and the all-out sprint (AOS).

HR, heart rate; HR_{Max}, the highest measured heart rate; HR_{Max}, the highest value measured during all tests; VO_2, oxygen uptake; Peak HR/VO_2, the highest HR/VO_2 measured during the specified bout; VO_{2Max}, the highest 30-s moving average measured (based on 10-s mixing chamber values) during the incremental maximum test; Rs, Spearman's rank order correlation coefficient; P_S, p-value for Spearman's rank order correlation;%DiffVO_{2Peak}, the difference between peak values of relative oxygen uptake (%VO_{2Max}) in the main part of the mass-start and during the AOS; %DiffHR_{Peak}, the difference between peak values of relative heart rate (%HR_{Max}) in the main part of the mass-start and during the AOS; pp, percentage points; R_P, Pearson's correlation coefficient; and P_P, p-value for Pearson's correlation coefficients.

incline, allowing us to study the underlying physiological and biomechanical mechanisms and generalize more on the impact of these variables on performance. Also, the inclusion of a 21-min low-intensity familiarization session before the mass-start strengthen our study by securing that all skiers were fully warmed up and familiarized with the equipment, the specific treadmill and inclines, as well as the track profile.

CONCLUSION

In this first study focusing specifically on performance related to the mass-start event in XC skiing by designing a protocol with variable intensity exercise with preset speeds and inclines followed by an AOS, the physiological and biomechanical variables fluctuated according to the changes in the simulated terrain, with a significant time-delay between a change in terrain and the physiological response and a lap-to-lap drift in $\%HR_{Max}$, TSI_{Arm} and power distribution between poling and ski push-offs. VO_{2Max} and skiing efficiency were significant performance-determining variables for simulated mass-start performance, enabling lower relative intensity during the initial phase, which likely caused less accumulation of fatigue when entering the final AOS. Subsequently, better performance was associated with more utilization of the demanding G3 sub-technique in the steepest uphill, and physiological reserves allowing better-performing skiers to utilize a larger portion of their aerobic potential and achieve longer CLs and higher speed during the AOS. Overall, our approach provides novel understanding of important mechanisms relevant for the mass-start events and provides a good starting point both for digging deeper into these mechanisms and opens for more applied approaches performed outdoors in future studies.

DATA AVAILABILITY STATEMENT

The data are not publicly available due to privacy concerns. Requests for accessing the dataset should be directed to TS, trine.seeberg@sintef.no.

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

All authors contributed to the overall concepts, protocol, sensor setup and framework presented in the manuscript, and to the revision and approval of the submitted version. DN, JD, KS, and PH conducted the data collection. TS, ØS, JK, and JT prepared the manuscript. DN calculated GE. JD calculated power distribution. JK synchronized the sensor data. JT contributed with framework for sub-technique classification. ØS provided expert knowledge of the field and was responsible for designing the experiment. Finally, TS developed model for cycle detection and sub-technique classification, explored and analyzed data, made figures and tables, and was responsible for preparing the manuscript.

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Race development and performance-determining factors in a mass-start cross-country skiing competition

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Introduction: Although five of six Olympic events in cross-country skiing involve mass-starts, those events are sparsely examined scientifically. Therefore, in this study, we investigated speed profiles, pacing strategies, group dynamics and their performance-determining impact in a cross-country skiing mass-start competition.

Methods: Continuous speed and position of 57 male skiers was measured in a six-lap, 21.8 km national mass-start competition in skating style and later followed up with an online questionnaire. Skiers ranked from 1 to 40 were split into four performance-groups: R1–10 for ranks 1 to 10, R11–20 for ranks 11 to 20, R21–30 for ranks 21 to 30, and R31–40 for ranks 31 to 40.

Results: All skiers moved together in one large pack for 2.3 km, after which lower-performing skiers gradually lost the leader pack and formed small, dynamic packs. A considerable accordion effect occurred during the first half of the competition that lead to additional decelerations and accelerations and a higher risk of incidents that disadvantaged skiers at the back of the pack. Overall, 31% of the skiers reported incidents, but none were in R1–10. The overall trend was that lap speed decreased after Lap 1 for all skiers and thereafter remained nearly unchanged for R1–10, while it gradually decreased for the lower-performing groups. Skiers in R31–40, R21–30, and R11–20 lost the leader pack during Lap 3, Lap 4, and Lap 5, respectively, and more than 60% of the time-loss relative to the leader pack occurred in the uphill terrain sections. Ultimately, skiers in R1–10 sprinted for the win during the last 1.2 km, in which 2.4 s separated the top five skiers, and a photo finish differentiated first from second place. Overall, a high correlation emerged between starting position and final rank.

Conclusions: Our results suggest that (a) an adequate starting position, (b) the ability to avoid incidents and disadvantages from the accordion effect, (c) tolerate fluctuations in intensity, and (d) maintain speed throughout the competition, particularly in uphill terrain, as well as (e) having well-developed final sprint abilities, are key factors determining performance during skating-style mass-start cross-country skiing competitions.

KEYWORDS

wearable sensors, GNSS - global navigation satellite system, skate, XC skiing, mass-start, cross-country skier

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Introduction

Cross-country (XC) skiing is a physiologically and technically demanding endurance sport in which speed, work rate, and energy expenditure fluctuate with constantly changing terrain (1, 2). Moreover, different competition formats in XC skiing vary in distance (i.e., approx. 1.5–50.0 km), style (i.e., classic and/or skating), and type of starting procedure (i.e., individual time trials or mass starts (3). Thus, the corresponding factors of race development (i.e., speed profiles across different terrains, pacing strategies and group dynamics) and their performance-determining impact can also differ considerably (2). Accordingly, understanding race-specific demands and associated performance determinants for each competition format is important for optimising training and race strategies. While individual time-trial competitions in both classic and skating-style are well-described in the literature (4–7) mass-start competitions, which represent the most common competition format, are only briefly examined.

Mass-start competitions in XC skiing were first introduced in the 2002 Olympics (8), and, in the most recent Olympics and World Championships, five out of six races were performed as head-to-head competitions, in which the winner is the first person to cross the finish line (8). In mass-start competitions, all skiers start together, often on narrow tracks with limited possibilities to advance in the field. Accordingly, tactical choices are crucial but may consequently influence physiological and biomechanical demands (8, 9). For example, changing position in a narrow track across fluctuating terrain, which induces rapid changes in work rate, requires both tactical and technical flexibility (8).

In mass-start XC skiing competitions, tactical flexibility may be particularly beneficial not only for advancing within the pack of skiers, but also for avoiding incidents and disadvantages caused by the accordion effect, which is known to occur in traffic and has been described in road cycling (10, 11). Briefly, the accordion effect occurs when competitors in front have to reduce speed but soon after accelerate, then the fluctuation in speed propagates backwards and typically increases further back in the pack (10, 11). Although the accordion effect has not been described in XC skiing, the large pack of skiers in mass-start competitions, combined with narrow tracks and fluctuating terrain, likely creates such an effect.

The influence of other competitors complicates individual pacing strategies more in mass-starts than in individual time-trial competitions (12). In mass-start races in mountain biking (13–15) and running (16), most competitors normally follow the leaders for as long as possible in order to benefit from the drafting effect and thereby improve their chances of winning, as may also be the case in XC skiing. At the same time, in XC skiing time trials, more than 50% of the total time is spent uphill (1, 6), which is the most performance-differentiating terrain (6, 17–19). Even though the influence of different terrain on overall performance in mass-start competitions has not been explored, a recent study investigating physiological responses during a laboratory-simulated mass-start competition revealed that the steepest and longest uphill segments were most performance-differentiating (20).

Against that background, the aim of our study was to investigate speed profiles, pacing strategies, group dynamics and their performance-determining impact in a XC skiing mass-start competition.

Materials and methods

Participants and design

The study was conducted in Gjøvik, Norway, on the 29th of January 2022 during a mass-start XC skiing competition in the skating style for senior men in the Norwegian National Cup Series. The skiers were recruited in collaboration with the event organisers after receiving information in the team captains meeting two days before the competition and during the distribution of bibs on the competition day. The 57 highest-ranked skiers (i.e., with the lowest FIS distance points) were equipped with global navigation satellite system (GNSS) sensors during the competition and afterward completed an online questionnaire addressing their strategies and experiences during the competition. Of the 57 skiers recruited, the 42 who finished within top 45 were included in our analyses. However, four of these (i.e., ranks 3, 7, 8, and 26) had low-quality GNSS signals, while three (i.e., ranks 18, 42, and 43) did not wear GNSS sensors as they were not among the 57 highest-ranked skier. Therefore, to include speed-profiles from all 45 skiers, we developed a method to synthesise data regarding position and time along the racecourse for those seven skiers with missing speed profiles; we derived a model using a deep learning approach (i.e., a machine learning) with the official race timing (i.e., 17 points along the racecourse) of the 38 skiers with speed profiles of adequate quality as input data. To group skiers by performance level, the top 40 skiers were divided into four groups based on their final rank in the race: R1–10 for ranks 1–10, R11–20 for ranks 11–20, R21–30 for ranks 21–30, and R31–40 for ranks 31–40. Skiers with synthetic position data were excluded from calculations of speed, while skiers ranked 41–45 were not placed in any performance-based group but were nevertheless included in the study to visualise a more realistic pack dynamic. We defined a *pack* as a group of skiers in which the gap between consecutive skiers is less than 3 s. The skiers' self-reported anthropometrics, along with the performance level of the top 45 skiers ($n = 42$) and the four performance-based groups, are presented in **Table 1**.

Measurements

The skiers were equipped with 10 Hz GNSS sensors (AdMos, Advanced Sports Instruments, Lausanne, Switzerland), a multisensory device comprising an inertial measurement unit in addition to the GNSS sensor, previously validated in alpine skiing (21). The sensors were placed on the skiers' backs, attached to the inside of the race bibs in customised pockets. To assess the accuracy of the GNSS device in that position, the times from the GNSS measurements were compared with the official split times provided by the organiser, giving a mean offset of less than 0.01 s with standard deviation (SD) 0.30 s over all 17 split times and 42 skiers. Within three weeks (6 ± 5 days) after the competition, the skiers ($n = 42$) completed an online questionnaire gathering self-reported anthropometrical characteristics as well as quantitative and qualitative data concerning planned and actual tactics during the competition, speed profiles, and perceived opportunities and challenges. The first six quantitative items referred to the skiers' strategies prior to the competition, whereas the following 11 referred to their experiences during the competition. For all items, the skiers rated their agreement on a 10-point scale (1 = *I do not agree at all*, 10 = *I agree completely*). Meanwhile, the six qualitative items referred to additional strategies prior to and experiences during the competition. The questionnaire was aligned with the objective sensor data and made by an expert group consisting of experienced coaches and researchers in the field. In addition, pilot tests were performed in front of the competition to assure that the questions were relevant and understandable.

Data processing

The sensor data was processed using MATLAB version R2020a (MathWorks Inc., Natick, MA). A 3D profile of the 21.8 km racecourse was developed based on the GNSS data by averaging data indicating the location and elevation of all skiers during all laps with a resolution of 1 m along the racecourse, after which the individual GNSS tracks were fitted to the racecourse. Segment times were calculated using the time mapped to the racecourse, while segment speed was calculated as course distance divided by time in the respective segments. The racecourse was divided into uphill, flat, and downhill segments based on position and altitude along the course, following a previously described procedure (5). The total uphill, flat, and downhill sections constituted 37.2%, 20.4%, and 42.4% of the total racecourse distance, respectively. To enable lap-to-lap analyses, a 3,550 m long lap course, with a maximal height difference of 42 m and a total climb of 114 m, was defined for Laps 2–6 by excluding the first few metres from the start and finish line. This lap was further divided into 14 segments (S1–S14) based on the type of terrain; **Figure 1** shows a 2D elevation profile and **Figure 2** a 3D visualisation of the lap course. A separate lap course was developed for Lap 1, which was shorter than the other laps; that lap course was 3,170 m long, with a maximal height difference of 21 m and total climb of 93 m, and, for the skiers' safety, excluded the steepest downhill segment (S5), one with a sharp curve, and the corresponding uphill (S6). Thus, Lap 1 consisted of 12 of the 14 sections from Laps 2–6.

Statistical analysis

All continuous measures are presented as mean ± SD. The Shapiro–Wilk test and the visual inspection of histograms were used to assess the normal distribution of the continuous variables. Between-group comparisons for each segment and lap and between-lap comparisons for each segment and group were performed using one-way ANOVA. In cases of statistically significant differences between groups, Tukey's post hoc analysis was conducted for comparison. Correlations between start position and final rank were calculated using Spearman's rank test.

The quantitative data from the questionnaire, reported on a 10-point scale, were presented as median and interquartile

TABLE 1 Anthropometrics and performance levels [mean value ± standard deviation (mean limits of confidence)] of the analyzed cross-country skiers in a 21.8 km mass-start competition, both overall and for the different performance-groups.

Variable	All R1–45 ($n = 42$)	R1–10 ($n = 10$)	R11–20 ($n = 10$)	R21–30 ($n = 9$)	R31–40 ($n = 10$)
Age (years)	24 ± 3 (23,24)	26 ± 3 (24,29)	23 ± 2 (21,24)	24 ± 2 (22,26)	22 ± 2 (21,23)
Body height (cm)	182 ± 6 (168,186)	178 ± 5 (174,181)	182 ± 3 (169,181)	185 ± 5 (181,189)	182 ± 7 (177,188)
Body mass (kg)	75 ± 5 (74,77)	72 ± 3 (70,74)	77 ± 3 (75,79)	78 ± 4 (74,81)	75 ± 5 (71,79)
Body mass index (kg·m^2)	22.7 ± 1.0 (22.4,23.0)	22.9 ± 0.6 (22.1,23.4)	23.3 ± 1.1 (22.4,24.1)	22.6 ± 0.9 (21.9,23.3)	22.5 ± 0.8 (21.9,23.1)
FIS distance points	47.6 ± 18.3 (41.9, 53.3)	26.1 ± 6.5 (21.5,30.8)	41.5 ± 11.4 (34.5. 53.2)	55.5 ± 12.7 (44.0,62.4)	60.5 ± 15.2 (52.5, 73.5)

R1–10 denotes ranks 1–10, R11–20 ranks 11–20, R21–30 ranks 21–30, and R31–40 ranks 31–40.

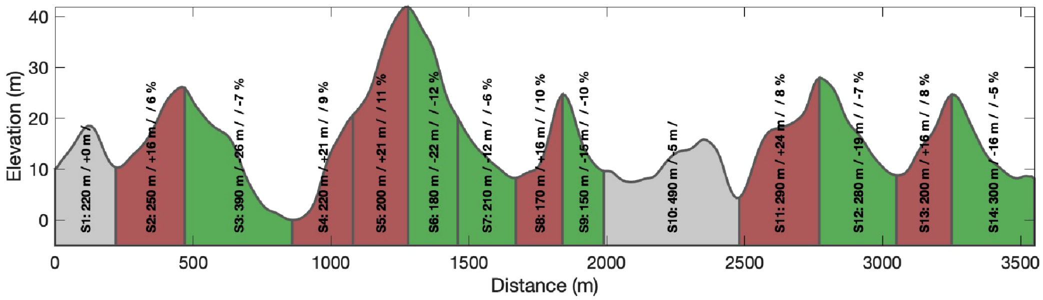

FIGURE 1
Two-dimensional profile of the racecourse used on Laps 2–6 in a 21.8 km cross-country skiing mass-start competition, showing elevation [m] as a function of lap-distance divided into different terrain segments (S1–S14) with segment distance [m], climb [m], and inclination [%] visualised. Lap 1 was shorter than the other laps but consisted of all segments except S5 and S6. The uphill segments are displayed in red, flat segments in grey, and downhill segments in green.

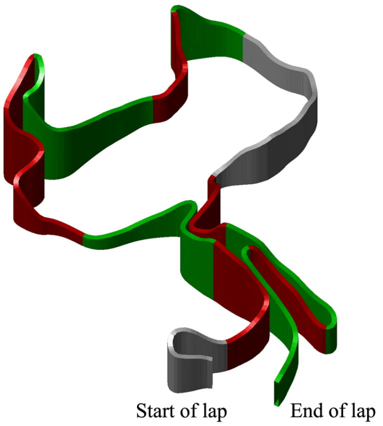

FIGURE 2
Three-dimensional visualisation of the racecourse used on Laps 2–6 in a 21.8 km cross-country skiing mass-start competition. The uphill segments are displayed in red, flat segments in grey, and downhill segments in green.

range (IQR). Between-group differences for each item were examined using an independent sample Kruskal–Wallis *H* test, and, if statistical differences were found, then pairwise post hoc tests were performed to identify the differences. By contrast, the qualitative data were assessed and presented at the group level. Following a simplified thematic analysis, encoded thematic statements made by three or more skiers in the same group were summarised and are presented among the results.

The level of statistical significance was set at an α-level of .05. All statistical analyses were performed using SPSS version 26 (SPSS Inc., Chicago, IL, United States).

Due to extensive statistical analyses with multiple comparisons, we decided to exclude some of the *p*-values. This was done for readability reasons and none of the excluded values were related to the main findings of this study. The remaining statistical findings are presented as following: Significant differences ($p < .05$) in average lap speed between neighbouring performance-groups are shown with superscript in the speed profile figures for the full lap, for flat, downhill and uphill terrain, and for all of the specific segments. Statistical comparison of average speed between laps for the different performance groups are given in **Table 2**, while the overall trends for corresponding differences across terrain types and segments are presented in the text. For the quantitative data in the questionnaire, the *p*-values for the between-group comparisons are presented in **Table 3**, while the significant differences ($p < .05$) between groups using pairwise post hoc tests are visualized using superscript.

Results

Start

Of the 143 skiers who started the race, 121 finished. Approximately 100 m after the starting line, the time from the front to the end of the field exceeded 16 s. **Figure 3** shows the final rank as a function of starting position, with the 45 skiers analysed marked in green (i.e., with GNSS-based speed profiles) and blue (i.e., with synthetic speed profiles). The correlation between the starting position and final rank of the 45 skiers analysed and all 121 skiers who finished the race were $\rho = .78$ and $\rho = .88$, respectively (both $p < .001$). The final rank of 80% of the top 45 skiers was within ±15 ranks of their starting position.

TABLE 2 Differences in average speed [m/s] between laps (white cells) with corresponding p-values (grey cells) for the different performance groups in a 21.8 km mass-start competition in cross-country skiing.

R1–10	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6	R11–20	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6
Lap 2		<.001	.393	<.001	.965	**Lap 2**		.055	.008	<.001	<.001
Lap 3	−0.12*		.027	.58	.001	**Lap 3**	−0.11		0.055	<.001	<.001
Lap 4	−0.04	0.07		.001	.782	**Lap 4**	−0.14*	−0.03		<.001	<.001
Lap 5	−0.15*	−0.03	−0.11*		<.001	**Lap 5**	−0.36*	−0.25*	−0.22*		.962
Lap 6	−0.02	0.10*	0.03	0.14*		**Lap 6**	−0.33*	−0.22*	−0.19*	0.03	
R21–30	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6	**R31–40**	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6
Lap 2		.024	<.001	<.001	<.001	**Lap 2**		<.001	<.001	<.001	<.001
Lap 3	−0.18*		<.001	<.001	<.001	**Lap 3**	−0.31*		<.001	<.001	.035
Lap 4	−0.47*	−0.29*		.324	1.00	**Lap 4**	−0.52*	−0.21*		.851	.577
Lap 5	−0.58*	−0.40*	−0.10		.391	**Lap 5**	−0.56*	−0.25*	−0.05		.110
Lap 6	−0.48*	−0.30*	−0.01	0.10		**Lap 6**	−0.44*	−0.13*	0.07	0.12	

R1–10 denotes ranks 1 to 10, R11–20 ranks 11–20, R21–30 ranks 21–30, and R31–40 ranks 31–40.
*Denotes that the values were statistically significant ($p < .05$).

Time behind winner and the formation of dynamic packs

Individual skiers' times behind the winner, along with continuous speed profiles for the lower-performing groups compared with the best-performing group, are displayed in Figure 4. The figure visualises where the skiers lost time to the winner and shows that all top 45 skiers stayed together in a large pack until 2.3 km, when the pack split into a leader pack and a second pack of skiers who were not able to follow the leader pack. Thereafter, those packs dynamically split and regrouped into smaller packs of two to eight skiers, with some single skiers between packs. This dynamic pack formation, which strongly related to the course's elevation profile (Figure 5A), is visualised as intermediate ranks (Figure 5B) and time behind the current leader (Figure 5C).

Accordion effect

An accordion effect was observed in the first four laps of the competition, particularly in the transition area from downhill or flat terrain to the steepest uphill segments (e.g., from S3 to S4 and from S10 to S11). Figure 6 visualises the effect by showing the number of skiers within 5 or 10 s from the current leader (Figure 6B), as well as the time gap between R1–10 and R11–20, R21–30, and R31–40 (Figure 6C) along the course profile (Figure 6A).

Pacing profiles

Average lap speed for the different performance-based groups with corresponding statistics are shown in Figure 7 "Full lap" and Table 4, respectively. Although speed during Lap 1 could not be compared directly to speed during other laps, the average speed for the parts of the course that could be directly compared across laps (i.e., aggregated average speed for segments S1–S4 and S9–S14), was significantly higher during Lap 1 than during the other laps for all groups ($p < .001$). Later, for R1–10, a relatively even lap speed emerged during Laps 2–6. For R11–20, lap speed was also even during Laps 2–4 but decreased in Laps 5 and 6, whereas R21–30 and R31–40 had reversed J-shaped pacing profiles, with gradually reduced lap speeds from Lap 2 to Lap 4 that evened out in Laps 5 and 6 (statistics given in Table 4). On average, R31–40, R21–30, and R11–20 lost the leader pack during Lap 3, Lap 4, and Lap 5, respectively.

Lap speed for the different terrains is shown in Figure 7 which also shows significant differences ($p < .05$) in lap speed between neighbour performance-groups with superscript. The overall trend was that average lap speed decreased lap-to-lap both for flat and downhill terrain but had a similar lap-to-lap variation as the average lap speed for uphill terrain.

Lap speed for each segment is shown in Figure 8. The general trend was that variation in lap-to-lap speed across uphill, downhill, and flat segments was similar to the respective variation in the lap-to-lap speed in the corresponding terrains shown in Figure 7. However, during Laps 4 and 5, the best-performing skiers increased the

TABLE 3 Median (interquartile range) of the quantitative data in the questionnaire filled out after a 21.8 km mass-start competition in cross-country skiing, both overall (n = 42) and within the different performance-groups, including the p-values for the between-group comparisons using the Kruskal–Wallis Test (KWT).

How well do you agree with the following statements about your planned strategies for the competition (plan) and execution during the competition (race) on a scale from 1 to 10?		Total	R1–10	R11–20	R21–30	R31–40	KWT
Open with an individually optimized speed *Scale: 1 (do not agree) 10 (fully agree)*	Plan	5.0 (5.0)	5.5 (4.5)	7.0 (5.0)^{c}	3.0 (3.0)^{b,d}	6.5 (3.0)^{c}	0.01
	Race	7.0 (4.0)	7.0 (4.5)	8.0 (2.0)	4.0 (4.3)	6.0 (4.3)	0.22
Open with the leader-pack and try to follow as long as possible *Scale: 1 (do not agree) 10 (fully agree)*	Plan	10.0 (4.0)	10 (2.5)	10.0 (4.5)	10.0 (1.3)	8.0 (6.5)	0.13
	Race	9.0 (3.0)	9 (2.5)	9.0 (3.0)	10.0 (1.3)	7.5 (6.8)	0.12
Open at a speed I could sustain throughout the race without “hitting the wall” *Scale: 1 (do not agree) 10 (fully agree)*	Plan	5.0 (4.0)	3.5 (3.5)	7.0 (4.0)^{c}	3.5 (4)^{b,d}	5.5 (4.8)^{c}	0.03
	Race	6.0 (5.0)	9.0 (5.5)	6.0 (4.5)	3 (5.3)	6.0 (4.8)	0.10
Open with a faster speed than optimal in order to draft behind other skiers *Scale: 1 (do not agree) 10 (fully agree)*	Plan	6.0 (5.0)	4.0 (5.0)^{c}	5.0 (4.5)	9.5 (2.5)^{a}	5.5 (6.3)	0.02
	Race	7.0 (5.0)	3.0 (5.0)^{c}	5.0 (3.0)	8.5 (3)^{a}	7.0 (6.3)	0.01
Ski controlled/conservative in uphills, even when falling behind *Scale: 1 (do not agree) 10 (fully agree)*	Plan	5.0 (4.0)	7.0 (3.0)	4.0 (5.5)	5.0 (1.8)	4.0 (5.8)	0.20
	Race	6.0 (4.0)	7.0 (4.0)	6.0 (5.0)	7.0 (3.0)	5.0 (4.8)	0.06
Stay behind other skiers throughout the entire race to save energy, i.e., avoid being at the front *Scale: 1 (do not agree) 10 (fully agree)*	Plan	8.0 (5.0)	7.0 (4.5)	9.0 (5)	8.0 (4.8)	6.0 (8.3)	0.87
	Race	7.0 (5.0)	8.0 (5.0)	6.0 (5.5)	8.0 (4.8)	7.0 (8.3)	0.79
Question:							
How fit did you feel today? *Scale: 1 (very poor) 10 (very good)*	Race	7.0 (2.0)	7.0 (2.0)	7.0 (1.5)	7.0 (2.3)	5.5 (4.3)	0.39
To what extent were you able to follow the planned strategy? *Scale: 1 (not at all) 10 (fully)*	Race	6.0 (4.0)	8.0 (1.5)^{d}	7.0 (4.5)^{d}	5.5 (3.3)^{d}	3.5 (2.8)^{a,b,c}	<0.01
Did you copy movement patterns of skiers in front of you? *Scale: 1 (not at all) 1 (fully)*	Race	6.0 (4.0)	5.0 (5.0)	7.0 (3.5)	7.0 (2.3)	5.0 (4.5)	0.41
How was the glide of your skis compared to other skiers? *Scale: 1 (very poor) 10 (very good)*	Race	6.0 (4.0)	7.0 (3.5)^{d}	7.0 (5.5)^{d}	7.5 (3.5)^{d}	3.5 (3.5)^{a,b,c}	0.03
How satisfied are you with your performance? *Scale: 1 (not at all) 10 (fully)*	Race	7.0 (4.0)	7.0 (3.5)	7.0 (4.0)	7.0 (2.3)	4.5 (4.0)	0.12

R1–10 denotes ranks 1–10, R11–20 ranks 11–20, R21–30 ranks 21–30, and R31–40 ranks 31–40).
Plan, planned strategy; Race, race experience.
^{a,b,c,d}This value was significantly difference from the corresponding value of R1–10/R11–20/R21–30/R31–40.

segment speed in some segments relative to lower-performing skiers, as detailed in **Figure 8** where significant differences in corresponding speed-values between neighbour performance-groups are visualised.

Performance in different terrain

On average, the skiers spent 53.4 ± 0.4% of their overall time in uphill, 19.6 ± 0.2% in downhill, and 27.0 ± 0.3% in flat terrain. The correlations between overall time and time spent in uphill, flat, and downhill terrains were $R = .97$, $R = .84$, and $R = .87$, respectively (all $p < .001$). Compared with R1–10, the relative time loss for R11–20, R21–30, and R31–40 was 61.6%, 74.8%, and 62% going uphill; 11.4%, 11.6%, and 14.2% across flat terrain; and 26.9%, 13.6%, and 23.8% going downhill, all respectively.

Final sprint

When approaching the final km, the leader pack consisted of 10 skiers, and the outcome of the competition was decided in a final sprint. All top 10 skiers were within 19 s of each other, the top 5 skiers were within 2.4 s of each other, and a photo finish differentiated first from second place. **Figure 9** illustrates each skier’s time behind the winner during the final 1.2 km of the race (left) and the first two skiers crossing the finish line (right).

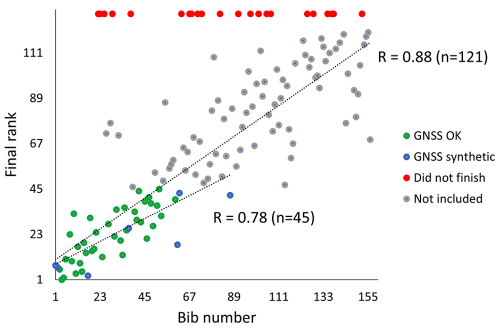

FIGURE 3
Final rank as a function of starting position (i.e bib number set by FIS distance points) in a 21.8 km cross-country skiing mass-start competition. The included skiers with adequate quality GNSS signals (GNSS OK) are visualised in green, skiers with synthetic speed profiles derived from a deep learning model explained in the methods section (GNSS synthetic) in blue, the skiers who did not finish in red and those not included in grey.

Questionnaire

Mean responses to the quantitative items on the questionnaire for all skiers and performance-based groups are shown in **Table 3**. The highest agreement among skiers concerned whether the strategy was to follow the leader for as long as possible even if the speed was too fast [10.0 (4.0) on a 1–10 point scale], with no between-group differences. Significant between-group differences ($p < .05$) emerged for only five of the items: two related to planned strategy, two related to race experience, and one related to both planned strategy and race experience, as detailed in **Table 3** shown as blue subscript.

The qualitative statements given by three or more skiers are presented in **Table 3**. Although the questionnaire did not specifically address the accordion effect, 50% of the skiers mentioned that challenge when responding to the open-ended items. The skiers in R1–10 stated that they had adopted a strategy of staying close to the leader in order to avoid the accordion effect, whereas skiers in the lower-performing groups explained that they had faced disadvantages related to the effect, as shown in **Table 3**.

Discussion

In our study, we investigated race development and performance-determining factors in a mass-start XC skiing competition and revealed five major findings. First, all skiers stayed together in a large pack until 2.3 km, at which point lower-performing skiers gradually lost the leader pack and formed new, dynamic packs of two to eight skiers. Second, average lap speed decreased from Lap 1 to Lap 2 and thereafter remained constant among the best-performing skiers, whereas lower-performing skiers gradually decreased their speed throughout the competition, particularly while crossing uphill terrain. Third, a considerable accordion effect occurred for lower-performing skiers during the first half of the competition. Fourth, 10 skiers sprinted for the win during the last 1.2 km, and a photo finish was needed to differentiate first from second place. Fifth and finally, the key factors determining performance were (a) having an adequate starting position (i.e., set by performance level) and (b) the ability to avoid incidents and disadvantages from the accordion effect, (c) tolerate fluctuations in intensity, and (d) maintain speed throughout the competition, particularly in uphill terrain, as well as (e) having well-developed final sprint abilities.

All skiers advanced together in a large pack in the initial 2.3 km of the competition, after which lower-performing skiers gradually lost contact with the leader pack and formed new, dynamic packs of two to eight skiers, with some single skiers between packs. Skiing in large packs is a unique feature of mass-start competitions and facilitates energetic benefits due to reduced ski–snow friction and aerodynamic drag (i.e., drafting) while skiing behind others. The latter is comparable to cycling, in which the aerodynamic drag can be as low as 50% of the drag for an isolated rider at the same speed when moving in a large peloton of cyclists (Blocken et al., 2018). Due to lower speed in XC skiing than in road cycling, the effect of reduced drag is expected to be lower but may play a significant role nonetheless, as demonstrated in classical XC skiing (22). That dynamic also emerged in the questionnaire responses in our study, in which saving energy by reducing aerodynamic drag was reported to be a key motivation for skiing together in packs. Several skiers also reported that it was advantageous to follow the technical patterns of the skier in front of them if they had similar patterns to their own. Even so, that potential advantage was perceived as being stressful if the technical pattern of the preceding skier was different. In terms of aerodynamics, it may be advantageous to synchronise the motion with the skier in front for two reasons. First, as shown in cycling (23) and speed skating (24), a synchronised movement is necessary to achieve a short separation from the skier in front and, in turn, less aerodynamic drag. Second, wind tunnel measurements from speed skating suggest that the reduction in aerodynamic drag is greater if competitors move in synchronised than in unsynchronised movements. Added to that, setting one's skis in the same tracks as the skier in front of them lowers the ski–snow friction for the skier behind. Taken together, the dynamic pack formation observed in our novel analysis of a mass-start XC skiing competition is consistent with what previously has been shown during mass starts in other endurance sport events such as running and triathlons (25, 26).

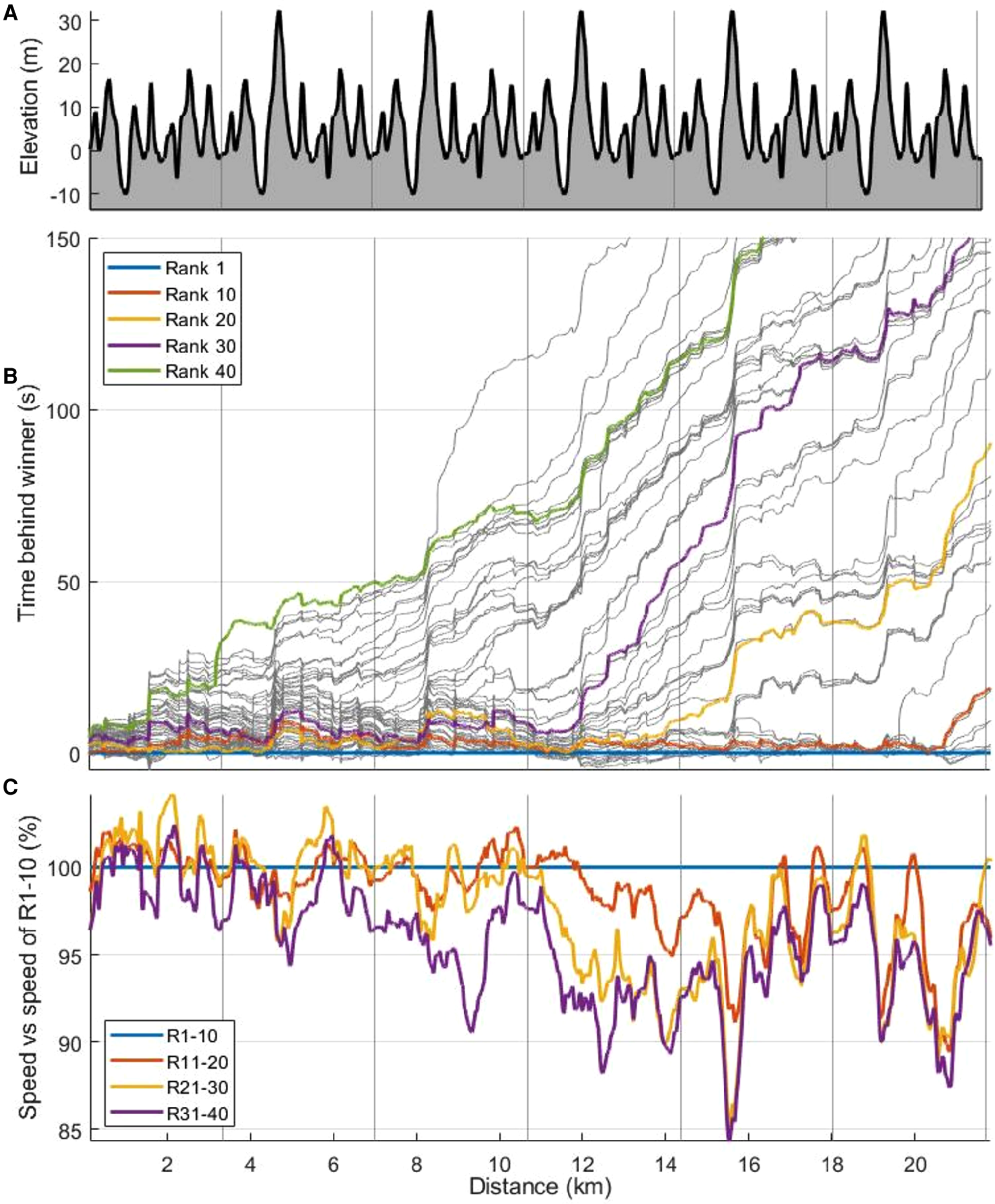

FIGURE 4
Elevation (A), time behind winner [s] for individual skiers (B) and continuous speeds (C) for the lower performance-groups (group R11–20, R21–30, and R31–40) compared to the first group R1–10 [%] as a function of distance [km] in a 21.8 km mass-start competition. R1–10 denotes ranks 1–10, R11–20 ranks 11–20, R21–30 ranks 21–30, and R31–40 ranks 31–40.

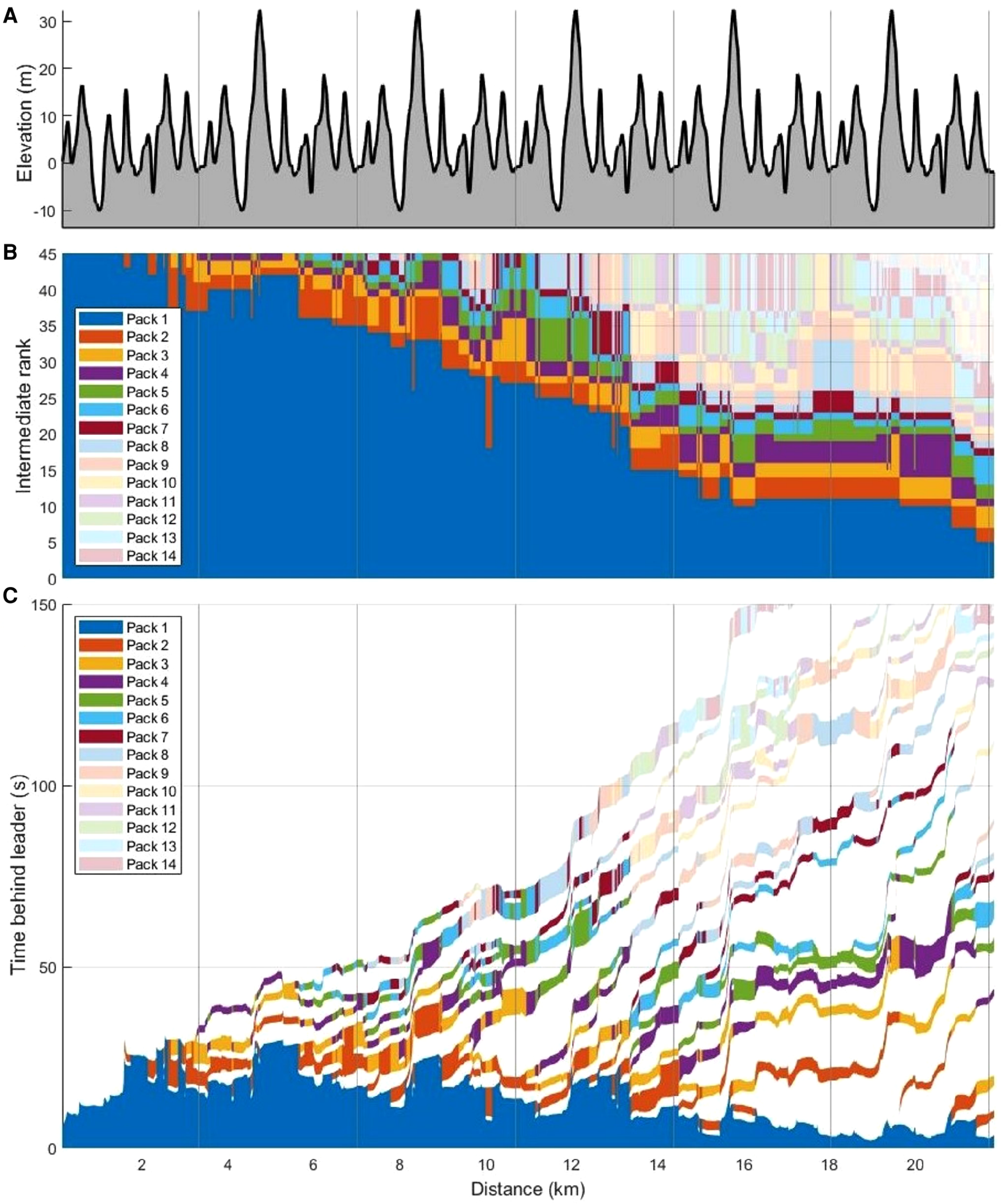

FIGURE 5
Elevation [m] (A), intermediate rank of skiers (B), and time [s] behind the current leader for each pack (C) as a function of distance [km] in a 21.8 km cross-country skiing mass-start competition. A pack of skiers included all consecutive skiers being less than 3 s apart and each pack is highlighted in different colours.

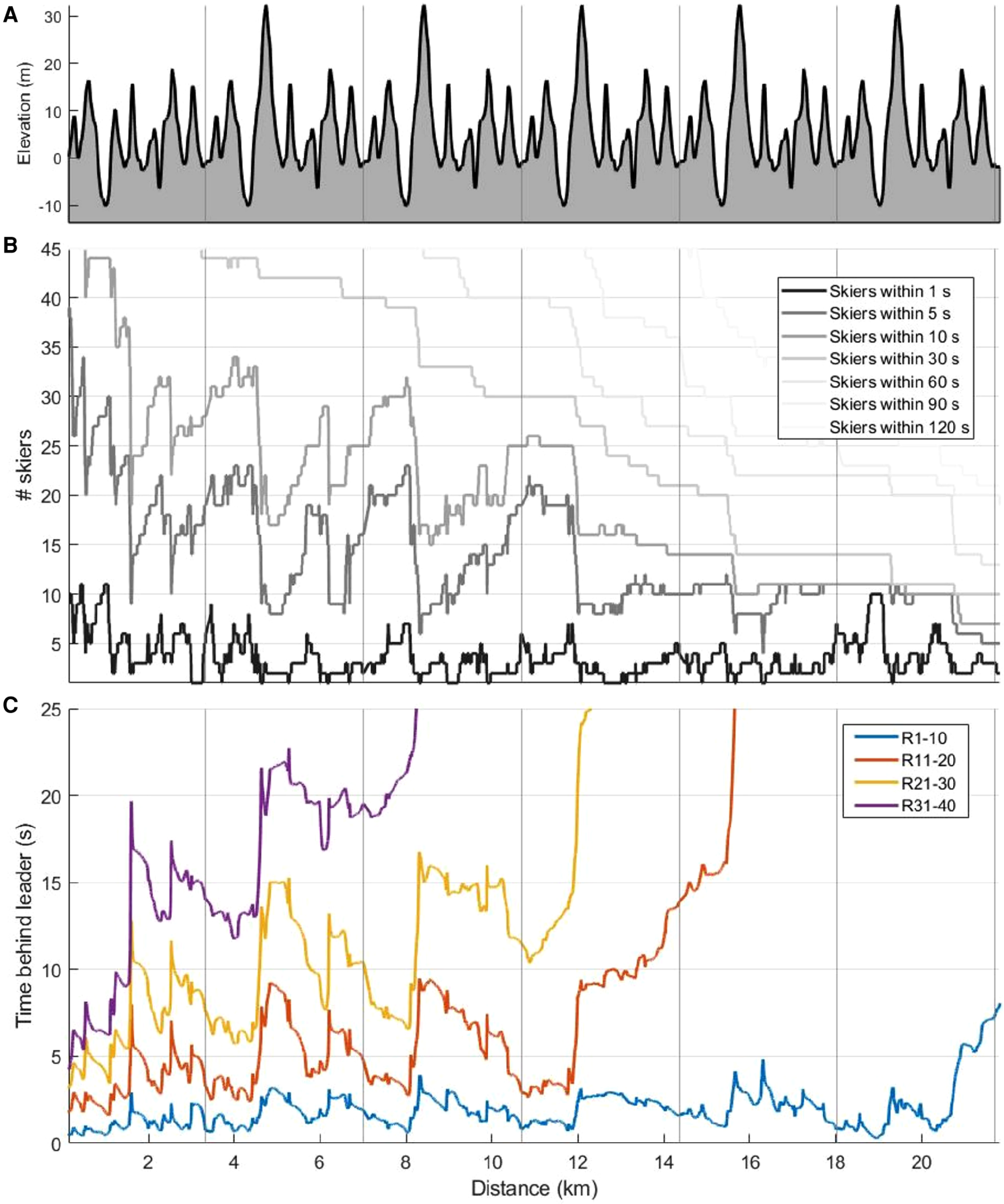

FIGURE 6
Elevation [m] (A), number of skiers within 1, 5, 10, 30, 60, 90 and 120 s from the current leader (B) and mean time behind the current leader for the different performance-groups (C) as a function of distance [km] in a 21.8 km cross-country skiing mass-start competition. Here, the accordion effect is clearly seen as fluctuating values from 0 to ∼12 km particularly in relation to the longest uphill in for the two lines "skiers within 5 s" and "skiers within 10 s", and for the three lowest performance-groups (R11–20, R21–30, R31–40). R1–10 denotes ranks 1–10, R11–20 ranks 11–20, R21–30 ranks 21–30, and R31–40 ranks 31–40.

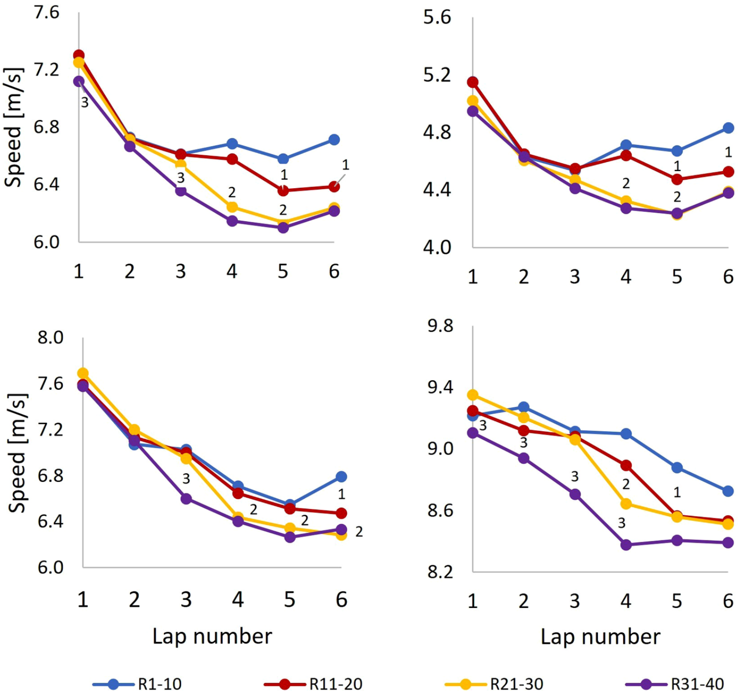

FIGURE 7
Average speed for full lap, uphill, flat, and downhill terrains as a function of lap-number for the performance-groups during a 21.8 km cross-country skiing mass-start competition. Note that Lap 1 was shorter than the other laps so speed for Lap 1 cannot be compared directly to speed on the following laps. Significant differences in corresponding speed-values between performance-groups are visualised in the figure. R1–10 (group 1) denotes ranks 1–10, R11–20 (group 2) ranks 11–20, R21–30 (group 3) ranks 21–30, and R31–40 (group 4) ranks 31–40. "*N*" on the plots denotes that speed-value for current group was significantly different from group *N*.

Moving in large packs may, however, also have disadvantages, particularly for skiers far behind in the pack. Several skiers in our study reported challenges with overtaking other skiers during the competition. Given that difficulty, a starting position in the front of the pack may be crucial for the final rank. However, because the starting position was based on previous performances (i.e., FIS distance points), we do not know how much of the variance can be explained by difficulties in overtaking competitors and thus cannot establish any cause–effect relationship. In a World Cup mass-start race in XC mountain biking, in which the size of the starting field was similar to that in our study (i.e., approx. 100–250 starters) and overtaking other athletes was shown to have similar challenges as in XC skiing, it was found that finishing position depended heavily on starting position (27). Typically, most competitors did not vary in finishing position compared with their starting position by more than ±15 places among elite men and ±10 places among elite women. A similar trend emerged in our study, in which the final rank of 80% of the top 45 skiers was within ±15 places of their starting position. In view of those results, future research should examine the advantages and disadvantages of starting position and whether changes in the starting order or restrictions on course layout are necessary for a fair competition.

The GNSS-based data revealed a considerable accordion effect at the back of the pack during the first half of the competition. Although the accordion effect previously has been described in road cycling (10, 11), our study is the first to reveal it in XC skiing. The effect likely depends on the racecourse, including both the elevation profile and the number and type of turns, along with the number of skiers who start together, the snow conditions, and the skiers' performance level. Our racecourse had several steep, short uphill segments, as well as some difficult sharp turns and many skiers at the same performance level. Thus, there was likely a particularly large accordion effect in the competition, which the skiers described as "large", "mad" and "extreme". R1–10 skiers reported adopting a strategy to avoid the accordion effect and showed the success of doing so by remaining at the front of the leader pack. By contrast, skiers

TABLE 4 Summary of encoded statements from the skiers (↑ illustrates the number of skiers) to the open questions in the questionnaire filled out after a 21.8 km mass-start competition in cross-country skiing, divided into different performance-groups.

R1–10	R11–20	R21–30	R31–40
Did you have any planned strategy that was not specifically addressed in the questionnaire?			
↑↑lie far forward in the pack to avoid the accordion effect ↑↑lie behind first part of the race and then try to speed up towards the end ↑overtake in flat /downhill terrain	↑↑lie far forward in the pack to avoid the accordion effect ↑overtake in flat/downhill terrain	↑↑↑ hang on to the leader-pack as long as possible, but not stress with overtakings on the first laps ↑lie far forward in the pack to avoid the accordion effect ↑overtake in flat /downhill terrain	↑↑↑ hang on to the leader-pack as long as possible, but not stress with overtakings on the first laps
What deviations did you do compared to the planned strategy, and why did it not do as planned?			
	↑↑lost time/positions due to an incident ↑↑was not in my best shape ↑bad skis	↑↑↑ lost the leader group earlier than planned ↑↑bad skis	↑↑↑↑↑↑↑↑↑ lost the leader group earlier than planned ↑↑↑↑was not in my best shape ↑↑↑ it was difficult to overtake ↑↑↑lost time/positions due to an incident ↑↑bad skis
Which advantages and/or disadvantages did you experience when skiing closely behind other skiers during the competition?			
Benefits: ↑↑↑↑↑↑ save energy due to less air resistance Disadvantages: ↑accordion effect first part of the race due to uneven speed	Benefits: ↑↑↑↑ save energy due to less air resistance Disadvantages: ↑↑↑ accordion effect first part of race due to incidents, stress, uneven speed, hilltops, coming into uphill segments, and narrow, technical terrain	Benefits: ↑↑↑↑ save energy due to less air resistance Disadvantages: ↑↑↑↑↑↑↑↑ accordion effect first part of race when the pack was large, particularly during two first laps, uneven speed, stress, risk of incidents	Benefits: ↑↑↑↑↑↑↑ save energy because of less air resistance Disadvantages: ↑↑↑↑↑ accordion effect first part of race due to uneven speed, too slow speed into uphill segments, incidents with skier in front
If you copied the movement pattern of skiers in front, which advantages and/or disadvantages did you experience?			
Benefits: ↑ more relaxed if skier in front had similar movement pattern as oneself ↑easier to stay close to the skier in front	Benefits: ↑↑↑↑ more relaxed/easier if skier in front had similar movement pattern as oneself Disadvantages: ↑↑↑ difficult if movement pattern is different to your own	Benefits: ↑↑↑easier to stay close to the skier in front Disadvantages: ↑↑↑ difficult if movement pattern is different to your own	Benefits: ↑↑↑↑↑ reduced risk of incidents in a large pack ↑↑↑easier to stay close to the skier in front Disadvantages: ↑↑↑↑difficult if movement pattern is different to own
Did you have any accidents during the competition?			
	↑↑↑ yes	↑↑↑↑↑ yes	↑↑↑↑ yes
Number of skiers who addressed the accordion effect in the open questions related to two categories, those who a) experienced it or b) strategically tried to avoid it.			
↑↑↑ strategically avoid	↑↑↑ experienced ↑strategically avoid	↑↑↑↑↑↑↑↑ experienced	↑↑↑↑ experienced

R1–10 denotes ranks 1–10, R11–20 ranks 11–20, R21–30 ranks 21–30, and R31–40 ranks 31–40.

in lower-performing groups reported disadvantages such as uneven speed, having too low a speed going into uphill terrain, stressful skiing, and a relatively high risk of accidents, all especially in the first part of the competition and when approaching uphill terrain, crossing hilltops, and navigating narrow, technical terrain. Moreover, those reports are supported by the GNSS-based data. Accordingly, the accordion effect prompted additional decelerations and accelerations for skiers in the back of the pack, which likely had considerable energy costs accompanied by the risk of premature fatigue. Given the obvious disadvantages of the accordion effect, skiers should try to reduce those disadvantages related to the effect during mass-start races. Possible strategies include staying far ahead in the group or, for lower-performing skiers, to leave the leader pack early and ski at their own pace in the first part of the competition in order to have sufficient energy to advance near the end of the competition.

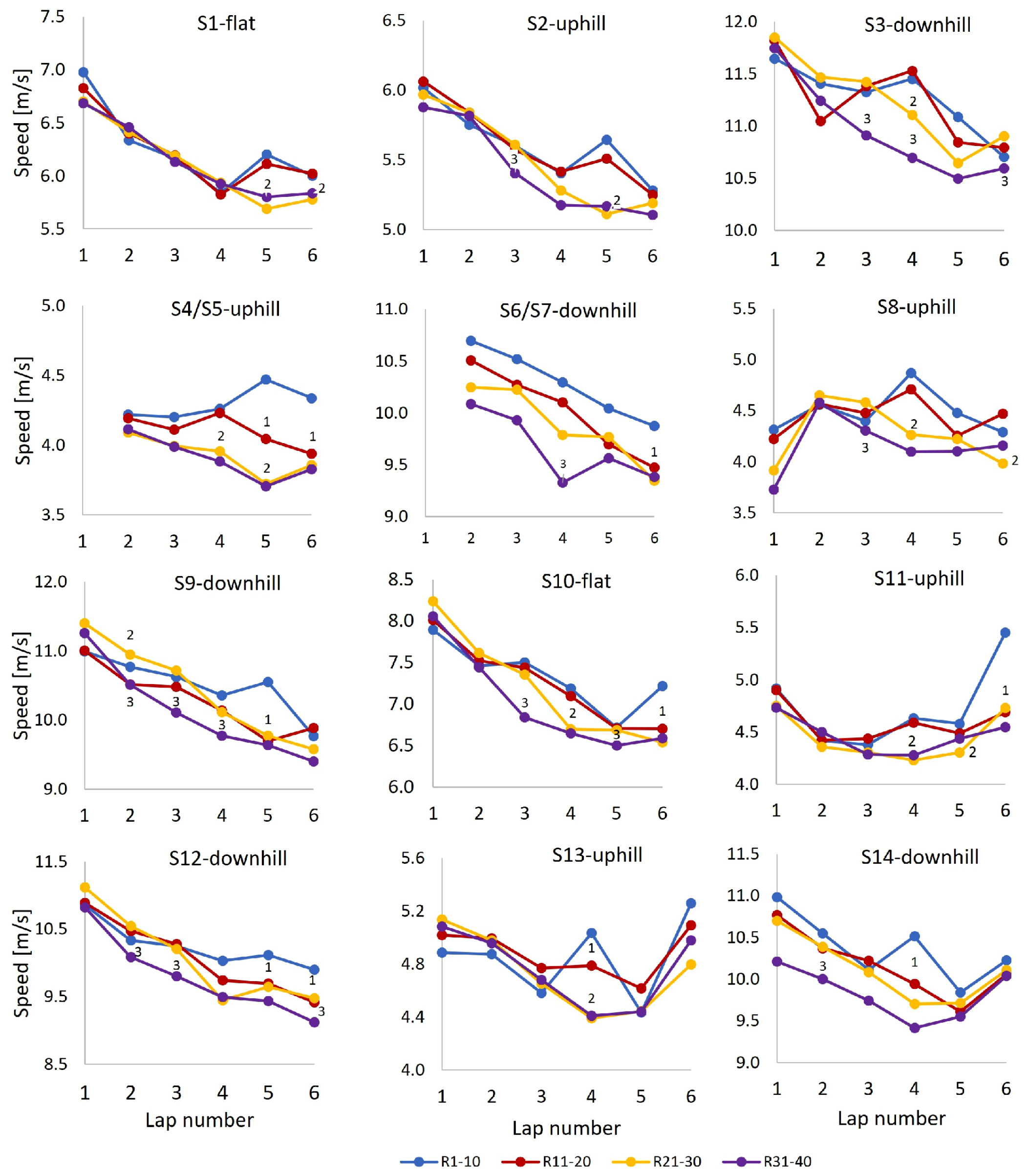

FIGURE 8
Average speed for each segment (S) as a function of lap number for the different performance groups during a 21.8 km cross-country skiing mass-start competition. Note that the speed for S8 on Lap 1 is lower than other laps due to lower speed into this segment since the downhill segment S6 was not included in Lap 1. Significant differences in corresponding speed-values between successive performance-groups are visualised in the figures. R1–10 (group 1) denotes ranks 1–10, R11–20 (group 2) ranks 11–20, R21–30 (group 3) ranks 21–30, and R31–40 (group 4) ranks 31–40. "*N*" on the plots denotes that speed-value for current group was significantly different from group *N*.

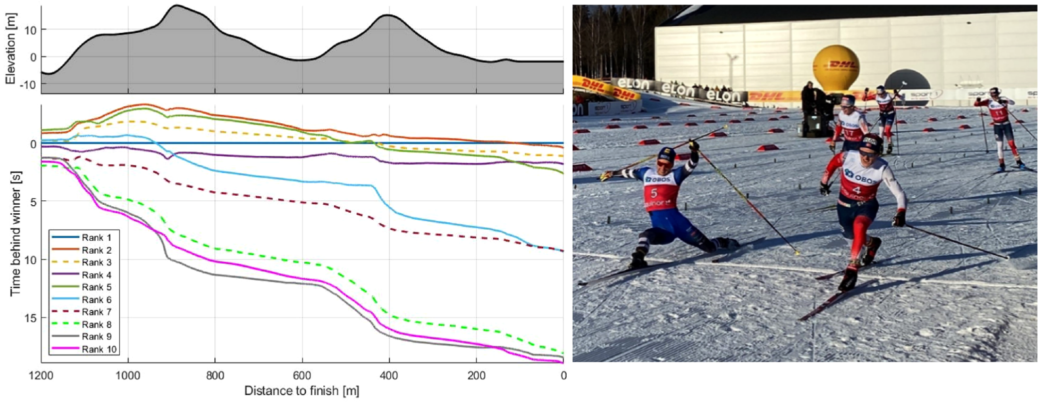

FIGURE 9
Time behind winner [s] for the top 10 skiers during the last 1.2 km of a 21.8 km mass-start competition (left) and picture of the two best skiers crossing the finish-line (right). Skier with final ranks 3, 7 and 8 have synthetic speed profiles derived from a deep learning model described in detail in the methods.

Among other results, several skiers in lower-performing groups reported many incidents and chaotic conditions in the back of the large pack. All told, 31% of the skiers reported being involved in at least one incident during the competition, but none of them were in the highest-performing group (R1–10). Therefore, the ability to avoid incidents seems to be crucial for the XC skier's final position.

Different pacing profiles were observed between the performance-based groups. After a fast start, skiers in the highest-performing group maintained their speed, while lower-performing groups gradually reduced their speed throughout the competition. As revealed by the questionnaire, the skiers had adopted the strategy of following the leader for as long as possible, even if they knew that they could not sustain the pace during all laps, and no between-group differences were found. Adopting that strategy led to positive pacing for lower-performing skiers, who likely had higher relative intensity during the first part of the competition. Such a pacing pattern may be less effective compared to more even pacing strategies shown to be beneficial in individual time trials in XC skiing (Losnegard, 2021). Indeed, that possibility aligns with findings from a laboratory-simulated mass-start competition (Seeberg et al., 2021) in which skiers who fatigued due to high uphill intensity were unable to maintain speed throughout the competition and/or reach their race peak VO_2/heart rate in the final sprint. The strategy of following the leader for as long as possible has also been observed during mass-start competitions in other endurance sports such as running and triathlon (25, 26) but never before in a mass-start XC skiing competition.

Although lap speed in the leader pack remained fairly constant during Laps 2–6, **Figure 8** shows that their speed temporarily increased during some of the segments in the second half of the competition. The leader pack also achieved a higher speed during the last part of Lap 4 and most of Lap 5, after which their speed decreased for a while before increasing again in the final sprint. Such pacing was also commented on in the questionnaire by a skier in R1–10: "Laps 4 and 5 were hard, as expected, but the first part of the last lap was easier. I wasn't able to keep up when the speed increased again". Accordingly, the ability to ski at high speed over time and tolerate rapid variations in speed and intensity during the last part of the competition distinguished the highest-performing skiers from their lower-performing peers. That trend aligns with the findings of a track-and-field study in which world-level competition data were examined to identify pacing and tactics across distances ranging from 800 m to 10 km (16). In that study, the medallists were able to not only maintain high speed throughout the entire competition but also accelerate near the end, whereas lower-finishing athletes were able to keep the pace temporarily before slowing down or being unable to accelerate as much as the medallists (16). Therefore, the requirement of tolerating high speed over time in addition to brief fluctuations in intensity is unique for XC skiing compared to other sports and particularly pronounced in mass-start competitions. It may therefore be beneficial to include such features in training sessions—that is, to practice variable intensities during long tempo sessions and develop final-sprint abilities in a fatigued state.

As consistently observed in time trials (6, 17–19) and a simulated mass-start in XC skiing (Seeberg et al., 2021b), uphill terrain was found the most performance-determining in the mass-start competition that we investigated.

However, there were also between-group speed-differences in the downhill terrain, in which R31–40 had a constantly lower average speed than all other groups in all laps. Several factors might have contributed to that difference in downhill performance—for instance, more incidents for lower-ranked skiers, less technical and tactical downhill skills, the lack of acceleration over hilltops (28, 29), and the accordion effect. In addition, skiers in R31–40 alone reported having less competitive skis than their peers. In contrast to uphill and downhill terrain, speed along flat terrain was similar in all groups except in the final lap, where R1–10 had higher speed than all other groups in the final sprint. Accordingly, uphill performance, as previously shown in time trials, was also a major determinant of performance in the skating-style mass-start competition that we examined.

The final sprint began 1.2 km before the finish line, when all skiers in R1–10 were together in the leader pack, before the current leader accelerated on a short uphill climb (S11), and three skiers immediately lost contact with the group. In the end, five skiers approached the final 400 metres in such proximity that the outcome of the competition was decided in an all-out-sprint. Ultimately, 2.4 s separated the top five skiers, and a photo finish was needed to differentiate first from second place. Accordingly, many competitors demonstrated a relatively similar performance level, and only marginal time differences distinguished them. Therefore, the ability to generate high speed at crucial moments and in the final sprint is another essential factor of performance in mass-start XC skiing competitions (1, 2, 20).

Strengths and limitations

The main strength of our study was its exploration of an official FIS-regulated mass-start XC skiing competition with more than 140 participants, including many nationally renowned and world-class skiers. We equipped 57 skiers with high-end GNSS sensors and were able to measure speed profiles for most of them. Although limited snow made the racecourse short and narrow, the temperature, snow conditions, and tracks remained relatively stable during the competition, thereby providing even conditions for all skiers. Another strength of the study was its combination of objective speed profiles with subjective information gained from the questionnaire. A limitation of the study, however, was that some GNSS sensors did not have adequate time in open space prior to the competition due to practical challenges. Therefore, the GNSS signals were poor for a few of the skiers. Additionally, GNSS technology is not accurate enough to detect relative positions in the field, which thereby limited our ability to examine group-based dynamics. A further limitation of the study was that the anthropometric data was self-reported. Also, the questionnaire made for the purpose of the study has not been validated and must be interpreted with caution.

Conclusion

This study provides the first scientific description of race development and performance determining factors in a mass-start XC skiing competition. All skiers initially clustered together in a large pack, after which weaker skiers gradually fell from the leader pack and formed new, dynamic packs of two to eight skiers throughout the competition. Following a fast start during Lap 1, at a time when skiers positioned themselves, lap speed decreased gradually for all skiers except the ones in the top 10, who achieved relatively constant lap times from Lap 2 and throughout the competition. As expected, performance in uphill terrain was the most pronounced factor differentiating skiers' performance. However, unlike in previous studies on individual time trials, other factors played a role, including a considerable accordion effect during the first half of the competition for the skiers in the back of the pack. Among the top 10 skiers, the final ranks were determined in the last 1.2 km, with a photo finish determining the winner of the competition. The key factors determining performance were (a) having an adequate starting position (i.e., set by performance level) and (b) the ability to avoid incidents and disadvantages from the accordion effect, (c) tolerate fluctuations in intensity, and (d) maintain speed throughout the competition, particularly in uphill terrain, as well as (e) having well-developed final sprint abilities. Thus, though mass-start competitions in XC skiing are determined by many of the same factors as individual time trials, and additionally require tactical flexibility, the ability to tolerate fluctuating intensity variations, and final sprint abilities.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

All authors contributed to the development of the overall concept, design the protocol, sensor setup and framework presented in the manuscript, and to the revision and approval of the submitted version of the manuscript. In addition, TMS, HW and RKT: conducted the data collection. JK: was responsible for processing the GNSS data. JK, HW and TMS: explored and analysed data, conducted the statistics, made figures and tables, while ØS was the main supervisor and guided the entire process. TMS: was the lead author and main responsible for writing and preparing the manuscript. All authors contributed to the article and approved the submitted version.

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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.

Publisher's note

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Paper 4

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Human Kinetics
ORIGINAL INVESTIGATION

Performance Effects of Video- and Sensor-Based Feedback for Implementing a Terrain-Specific Micropacing Strategy in Cross-Country Skiing

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Purpose: To investigate the performance effects of video- and sensor-based feedback for implementing a terrain-specific micropacing strategy in cross-country (XC) skiing. ***Methods:*** Following a simulated 10-km skating time trial (Race1) on snow, 26 national-level male XC skiers were randomly allocated into an intervention (n = 14) or control group (n = 12), before repeating the race (Race2) 2 days later. Between races, intervention received video- and sensor-based feedback through a theoretical lecture and a practical training session aiming to implement a terrain-specific micropacing strategy focusing on active power production over designated hilltops to save time in the subsequent downhill. The control group only received their overall results and performed a training session with matched training load. ***Results:*** From Race1 to Race2, the intervention group increased the total variation of chest acceleration on all hilltops ($P < .001$) and reduced time compared with the control group in a specifically targeted downhill segment (mean group difference: –0.55 s; 95% confidence interval [CI], –0.9 to –0.19 s; $P = .003$), as well as in overall time spent in downhill (−14.4 s; 95% CI, −21.4 to −7.4 s; $P < .001$) and flat terrain (−6.5 s; 95% CI, −11.0 to −1.9 s; $P = .006$). No between-groups differences were found for either overall uphill terrain (−9.3 s; 95% CI, −31.2 to 13.2 s; $P = .426$) or total race time (−32.2 s; 95% CI, −100.2 to 35.9 s; $P = .339$). ***Conclusion:*** Targeted training combined with video- and sensor-based feedback led to a successful implementation of a terrain-specific micropacing strategy in XC skiing, which reduced the time spent in downhill and flat terrain for intervention compared with a control group. However, no change in overall performance was observed between the 2 groups of XC skiers.

Keywords: GNSS, pacing, IMU, sensor performance, XC skiing

Cross-country (XC) skiing is an endurance sport performed outdoors in varying terrain and cold conditions, with competition formats ranging from 3-minute sprint races to 2-hour distance races. The race courses consist of ascending, flat, and descending terrain, designed so each of these sections is relatively short and lasts for less than a minute (typically ranging between 10 s and 35 s).[1] Accordingly, XC skiing involves constant variations in speed, external power, metabolic intensity, as well as frequent transitions between various subtechniques of the skating and classical style, and modification of cycle rate and length according to the course topography, conditions, and race dynamics.[2,3] Since all these parameters interplay, XC skiing is not only dependent on endurance capacity but also on technical and tactical skills.[2]

An essential factor in endurance competitions is to optimize the pacing strategy, that is, to use energetic resources as effectively as possible from start to finish.[4] The varying terrain in XC skiing requires a continuous decision-making process based on anticipation of effort, information about the course profile and snow conditions, as well as perception of the current physiological and psychological state. Accordingly, XC skiers employ a variable pacing pattern with higher metabolic rates and power production during uphill than flat and downhill terrain,[5,6] with the uphill sections being the most performance determining terrain.[7–10] To further improve performance, refining XC skiers' micropacing strategy, by adjustments of speed and/or transitions between subtechniques within or between terrain sections, can be beneficial. Still, only 2 previous studies have investigated different aspects of micropacing in XC skiing. A recent intervention study by Losnegard et al[11] found that skiers with a high start speed improved performance by employing a more even pacing strategy. Furthermore, Ihalainen et al[12] investigated micropacing strategies during a classical sprint time trial and showed that the instant speed during the acceleration phase over hilltops was

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significantly correlated with speed in the subsequent downhill section. This study also indicated that performance in downhill terrain influences overall performance, which is especially relevant when the margins between skiers are small.[12] Therefore, we hypothesize that increasing speed over specific hilltops to save time in the subsequent downhill without reducing speed in other parts of the track could improve XC skiing performance.

XC skiers typically perform training sessions on the specific race courses prior to competitions to optimize technical and tactical solutions. Still, the pacing strategies developed in such sessions are typically based on the experiences of the athlete and coach. In this context, objective feedback would be valuable for helping athletes and coaches to optimize micropacing strategies and thereby improve performance in the upcoming competition. Currently, objective feedback on speed and technical patterns can be gained from the combined use of various sensors with adapted signal processing and smart classification and detection models.[13–16] This could be combined with video that is recently reported as a promising tool for improving individual feedback when coaching large groups.[17] Therefore, the aim of this study was to investigate the performance effects of using video- and sensor-based feedback for implementing a terrain-specific micropacing strategy when preparing for an XC skiing competition.

Methods

Participants

Twenty-six (junior and senior) male skiers, classified as highly trained/national-level (Tier 3) athletes according to a recently developed classification framework,[18] volunteered to participate in the study and completed the protocol. The skiers were recruited from a high-school and university with a specialized study program for XC skiing in mid-Norway and had 6–10 years of experience as skiers (participant characteristics presented below).

Since the Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for such studies, the study was performed in accordance with the institutional requirements and in line with the Helsinki declaration. Approval for data security and handling was obtained from the Norwegian Center for Research Data (project number 700549) in front of the study. Prior to commencing the study, all skiers provided written informed consent to voluntarily take part in the study and were informed that they could withdraw at any time point.

Design

The study was performed in Meråker in an International Ski Federation–homologated sprint course (Grova, altitude 408 m.a.s.l) in April 2021. The skiers performed 2 simulated 10-km time-trial races (Race1 and Race2) in the skating technique separated by 48 hours. The competition consisted of 3 laps of 3.2 km and was performed with a self-selected lap-to-lap pacing strategy (ie, macropacing). The race course exhibited a varied topography based on a course profile divided into uphill (38%), flat (17%), and downhill (45%) sections, with a total climb of 306 m (3 × 102 m) (Figure 1). To avoid too many skiers in the course at the same time, a 5-minute start interval was used between skiers. After the first 15 skiers, there was a 30-minute break due to the number of available sensors. Prior to both races, the skiers performed warm-up procedures consisting of 1 lap of 3.2 km low-intensity skiing before performing two 20-m maximal speed ($V_{\max}$) tests in flat terrain, followed by two 20-m $V_{\max}$ tests in uphill terrain.

Intervention

After Race1, the skiers were randomly allocated into an intervention group (INT, n = 14, 20 [1] y, 78 [9] kg, 182 [8] cm, VO_2peak skate = 71.5 [4.5] mL·min^{-1}·kg^{-1}) or control group (CON, n = 12, 19 [1] y, 77 [1] kg, 183 [1] cm, VO_2peak skate = 72.4 [3.5] mL·min^{-1}·kg^{-1}), see Talsnes et al[19] for VO_2peak skate protocol. The groups were balanced for starting time, performance in segment 10 (S10; see Figure 1), and race performance; difference in total race time in Race1 for INT compared with CON was +9.7 s; 95% confidence interval (CI), −60 to 79.7 s; $P = .381$. Between races, INT received video- and sensor-based feedback through both a theoretical and a practical training session, while CON only received race results and performed a training session with the same duration and intensity, but no feedback on micropacing.

In the 45-minute theoretical group session, the speed profile (measured by GNSS) in S10 of each skier was shown along with the corresponding speed profile of the fastest skier (see example of slide in Figure S1 in the Supplementary Material [available online]). Subsequently, video footage of the first part of the same segment was shown for each skier, with a brief discussion with the skier on the potential technical and tactical improvements.

In the practical training session, the skiers performed S10 7 times and S12 6 times with different technical and tactical strategies, aiming to increase speed in the specific segments but without reducing speed in other parts of the track. Here, the skiers were instructed to perform a short acceleration phase on the hilltop with a focus on active propulsion in the last cycles before quickly going down in a tucked position. Immediately after each trial, the skiers got feedback on their speed from the photocells and technical performance based on visual observation from a coach. In the first and sixth trial for S10, and in the first trial for S12, they were instructed to simulate their strategy in Race1. During their final trial in both segments, they were instructed to employ what they had learned during the practical session and ski as they planned to do in Race2. The rest of the trials were used to practice different micropacing strategies. Results from the practical training session are provided in Table S1 in the Supplementary Material (available online).

Weather and Snow Conditions

The race course was machine groomed at the same time in the morning of all 3 days. Wind, air temperature, humidity, and atmospheric pressure were measured 3 times during each race using a local weather station (https://embed.metnet.no/?dash=Fh62OYQaAI). The weather at the stadium varied as follows during Race1: wind, 1.0 to 2.2 m·s^{-1}; air temperature, −1°C to 1.6°C; relative humidity, 98% to 88%; and atmospheric pressure, 102 to 1027 hPa, and Race2: wind, 0.0 to 3.0 m·s^{-1}; air temperature, 1.5°C to 6.0°C; relative humidity, 89% to 67%; and atmospheric pressure, 1037 to 1036 hPa. Snow friction was not measured throughout the races, but based on the overall results there was a lower friction coefficient during Race2 compared with Race1, which resulted in significantly higher speeds and better overall performances during Race2. The conditions also changed within both days, with light snow falling during parts of Race1 and the sun peeking through the skies during parts of Race2.

Instruments and Materials

The skiers used their own ski equipment, including poles, boots, and skis individualized to their preferences. They were instructed to prepare the skis with the same waxing ahead of each race.

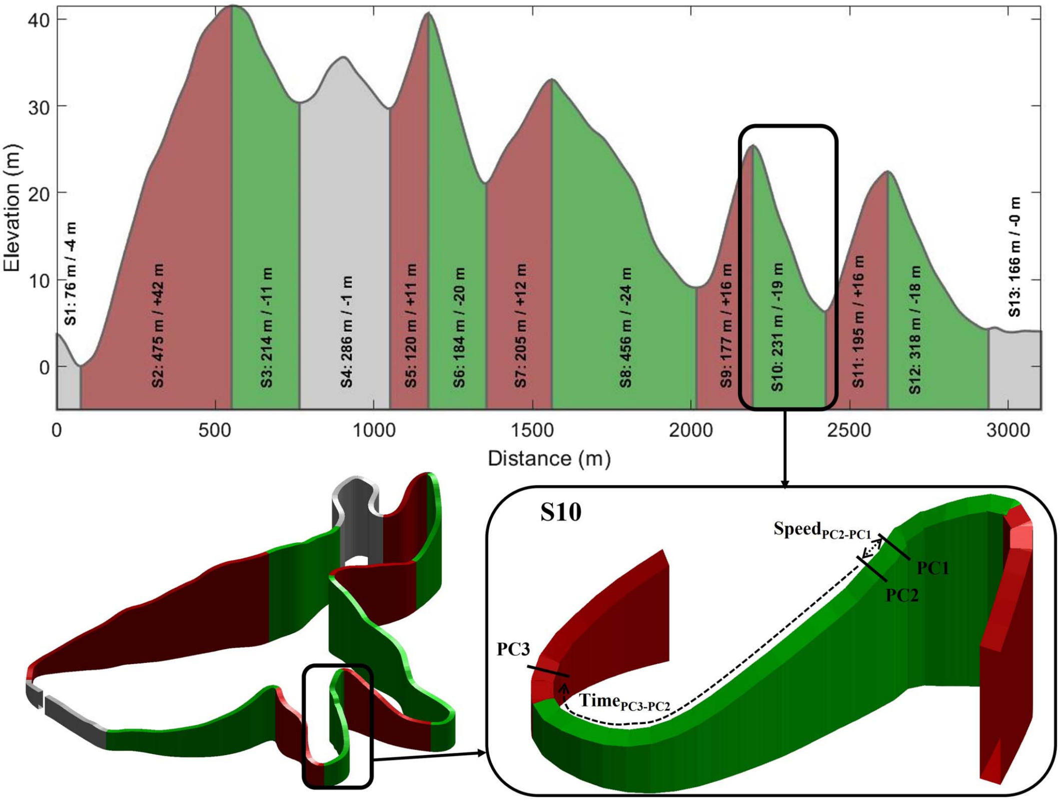

Figure 1 — The racecourse (3 × 3.2 km) used in both races in 2D divided into segments, in 3D and downhill segment 10 with placement of PCs and definition of the 2 derived measures from photocells; Speed $_{PC2–PC1}$ and Time$_{PC3–PC2}$. PC indicates photocell.

Course and elevation profiles (Figure 1) were determined with a differential global navigation system (Alpha-G3T, Javad GNSS Inc). Dual-frequency (L1 and L2) GPS and GLONASS signals were logged at 25 Hz, and a short baseline kinematic carrier phase differential GNSS solution was calculated using Justin (Javad GNSS Inc) postprocessing software.[20] Positions were smoothed using the differential GNSS solutions accuracy estimates as weighted into a spline filter.

During the races, each skier was equipped with a global navigation satellite system standalone receiver[21] (Optimeye S5, Catapult Sports) worn in a customized bib on the torso in an erect position that collected position at a sampling rate of 10 Hz. Garmin Forerunner 920XT/935 (Garmin Ltd) with an electrode belt measured heart rate at a sampling frequency of 1 Hz and is given as the percentage of HR$_{max}$, the highest heart rate obtained during the tests. Movement data of the chest were collected by an inertial measurement unit (IMU) fastened with velcro on the front of the electrode belt (GaitUp SA) and comprised of a 3D-accelerometer and 3D-gyroscope at 256 Hz, and a barometric pressure sensor at 64 Hz. Ratings of perceived exertion (RPE) were recorded with the 6- to 20-point Borg scale[22] immediately after the race.

During both races and in the practical training session, the performance in S10 was calculated based on photocell (PC) measurements obtained from a 2-way mesh radio transceiver (HC Timing, wiTiming) with 3 sets of 500-mW transmitters (HC Timing, wiNode), see Figure 1 for positions of the transmitters. Two measures were derived from the transmitters: (1) instant speed after the acceleration phase calculated by measuring the time in a 3-m segment (Speed$_{PC2–PC1}$) and (2) elapsed time from the speed measurement to the end of the downhill, that is, approximately the time the skier was in tucked position (Time$_{PC3–PC2}$). In addition, video of each skier passing S10 during the races was captured with video camera.

A different set of photocells (TC-Timer, Brower Timing Systems) was used to measure V_{max} flat, V_{max} uphill as well as the instant speed after the acceleration phase in S12 (Speed$_{PC2–PC1}$) during the practical training session.

Measurements and Data Exploration

Synchronization of Continuous Sensor Data. All IMU data were logged and time-synchronized during the protocol and later downloaded and analyzed offline in MATLAB (MathWorks). The IMU data from GaitUp and the GNSS sensor data from Catapult were synchronized by cross-correlating acceleration/gyroscope data recorded by the IMUs in both sensor systems. In addition, the heart rate data were correlated to the IMU data by cross correlation of the barometric sensor data in the GaitUp IMU and the Garmin watch.

Division in Downhill, Flat, and Uphill Terrain. The race course was divided into uphill, flat, and downhill terrain based on position and altitude data from DGPS measurements collected along the course, following the procedure described in Sandbakk et al.[9]

Total Variation of Chest Acceleration on Hilltops (totVarAcc). An accelerometery-derived measure that captures the intensity of both active poling and leg kick was used as an indicator of skier's biomechanical work intensity on the hilltops. The measure was based on the nonconstant part of the acceleration total signal power from the chest and is given by the following equation:

$$\text{totVarAcc} = \sum_{a\epsilon(x,y,z)} \left\{ \frac{1}{\text{N}} \sum_{i=1}^{\text{N}} \text{movvar}(a,\omega)_i \right\}.$$

Here a is the acceleration in the x,y,z-direction, N is the number of accelerometer samples, and movvar (MATLAB-function) is the gliding variance with window size $\omega = 5$ s—see Supplementary Material (available online) for details. The hilltop was defined from start of segment to the point where all subjects had transferred into tucked position determined for each hilltop by inspection of accelerometer data (S3 = 120 m, S6 = 60 m, S8 = 100 m, S10 = 100 m, S12 = 100 m).

Statistical Analysis

Shapiro–Wilk tests and comparison of histograms were used to assess the normality of the distributions of the variables, and Levene test was used to assess the homogeneity of variances in the different groups. An independent-sample t test was used for assessing between-group differences in relative change of total race time from Race1 to Race2 and for INT compared with CON. A paired t test was used to compare heart rate (mean [SD]) and Wilcoxon signed-rank test to compare RPE (median [interquartile range]) from Race1 to Race2. A linear mixed model with lap number (laps 1–3) and group/race day (with a common baseline on Race1; ie, Race1_All, Race2_INT, Race2_CON) as fixed factors and skier ID as a random factor was used to compare the relative change from Race1 to Race2 for INT compared with CON in the following parameters: Speed$_{\text{PC2–PC1}}$, Time$_{\text{PC3–PC2}}$, totVarAcc, time in S1:S13, the overall time in downhill, flat, and uphill terrain and the whole lap. Output parameters from the linear mixed model are reported as: (mean difference in improvement for INT versus CON; 95% CI, low to high; P value). Correlation between changes in performance for the skiers in INT from Race1 to Race2 (ΔSpeed$_{\text{PC2–PC1}}$, ΔTime$_{\text{PC3–PC2}}$, ΔRacetime, and ΔtotVarAcc) with VO$_2$peak skate and different race measures were calculated using Pearson correlation coefficient. For all relative group comparisons, the value for CON was set at 100%, and for all analyses, the level of statistical significance was set at $\alpha = .05$. RStudio version "2021.09.1 Build 372" with the 2 libraries "lme4" and "foreign" were used for linear mixed model analysis, while SPSS (version 26.0) was used for normality assessments, t test, Wilcoxon test, and regression analysis.

Results

Performance in the Specific Downhill Segment (S10)

Due to faster external conditions in Race2, all skiers had higher speed in Race2 compared with Race1 (Figures 2 and 3). However, the reduced time per lap from Race1 to Race2 in S10 was significantly higher in INT compared with CON: Time$_{\text{S10}}$ (−0.55 s; 95% CI, −0.9 to −0.19 s; $P = .003$), Speed$_{\text{PC2–PC1}}$ (0.74 m·s^{-1}; 95% CI, 0.53 to 0.94 m·s^{-1}; $P = .000$), and Time$_{\text{PC3–PC2}}$ (−0.63 s; 95% CI, −1.02 to −0.25 s; $P = .001$). With all 3 laps included, INT improved in total 1.65 seconds (7.5%) compared with CON in S10. The continuous speed plot (Figure 2) displays similar speed in both groups in Race1, while a substantial higher speed in INT versus CON occurs during the first part of the downhill and rest of the section in Race2.

TotVarAcc in S10 increased more for INT than CON from Race1 to Race2, the increase for INT compared with CON was 6.18 (m·s^{-2})^2 (95% CI, 4.48 to 7.87 [m·s^{-2}]^2; $P < .001$), see Figure 4 for individual values for each skier.

The improvement for the skiers in INT for Speed$_{\text{PC2–PC1}}$ ranged from 0.8 to 2.5 m·s^{-1} (9.4%–26.6%) and for Time$_{\text{PC3–P2}}$ from 2.0 to 5.4 seconds (10%–24.4%). In addition, the increase in totVarAcc correlated with ΔSpeed$_{\text{PC2–PC1}}$ and Time$_{\text{PC3–P2}}$ (Table 1). Also, for INT, there were no significant correlations between improvement in Speed$_{\text{PC2–PC1}}$, Time$_{\text{PC3–P2}}$, or total race time with the performance indicators (V_{max} flat/uphill or VO$_2$peak skate). However, the skiers that had lower preintervention Speed$_{\text{PC2–PC1}}$, Time$_{\text{PC2–PC1}}$, and total race time improved more than the other skiers (Table 1). Individual and mean values for Speed$_{\text{PC2–PC1}}$ and Time$_{\text{PC2–PC1}}$ are given in Table S2 in the Supplementary Material (available online).

Overall Performance and Performance in Different Terrain

The intervention group reduced time in S3, S4, S8, S10, and S12 compared with CON (Table 2), and totVarAcc increased more for INT compared with CON in all downhill segments (S3, S6, S8, S10, and S12; all $P < .001$), see Figure 4 and Table 2.

A higher relative improvement in INT versus CON was found in overall downhill (−14.4 s; 95% CI, −21.4 to −7.4 s; $P < .001$) and flat terrain (−6.5 s; 95% CI, −11.0 to −1.9 s; $P = .006$), while no significant differences were found for uphill terrain (−9.3 s; 95% CI, −31.2 to 13.2 s; $P = .426$) or overall race time (−32.2 s; 95% CI, −100.2 to 35.9 s; $P = .339$). No changes in percentage of HR$_{\text{max}}$ (INT: −0.54% [0.98%] point, $P = .058$; CON: −0.24% [1.41%] point, $P = .561$) or RPE (INT: 0.5 [1.25], $P = .527$; CON: 0.5 [1.75]; $P = .257$) from Race1 to Race2 were observed. Individual and mean values for the time used in the terrain types, total race time, percentage of HR$_{\text{max}}$, and RPE in Race1 and Race2 are displayed in Figure 3 and Table 2, while details are given in Tables S2 and S3 in the Supplementary Material [available online]. The continuous speed difference (mean lap value) between INT and CON according to the elevation profile and the time difference for each segment are displayed in Figure 5.

Discussion

The present study investigated the effects of video- and sensor-based feedback for implementing a specific micropacing strategy when preparing for an XC skiing competition. The intervention group significantly reduced time spent in the targeted downhill segment, along with shorter time spent overall in downhill and flat terrains, compared with the matched controls. However, no significant effects of the intervention were observed in uphill terrain or for overall race performance.

As expected, INT improved performance significantly more than CON in the specific downhill segment targeted during the

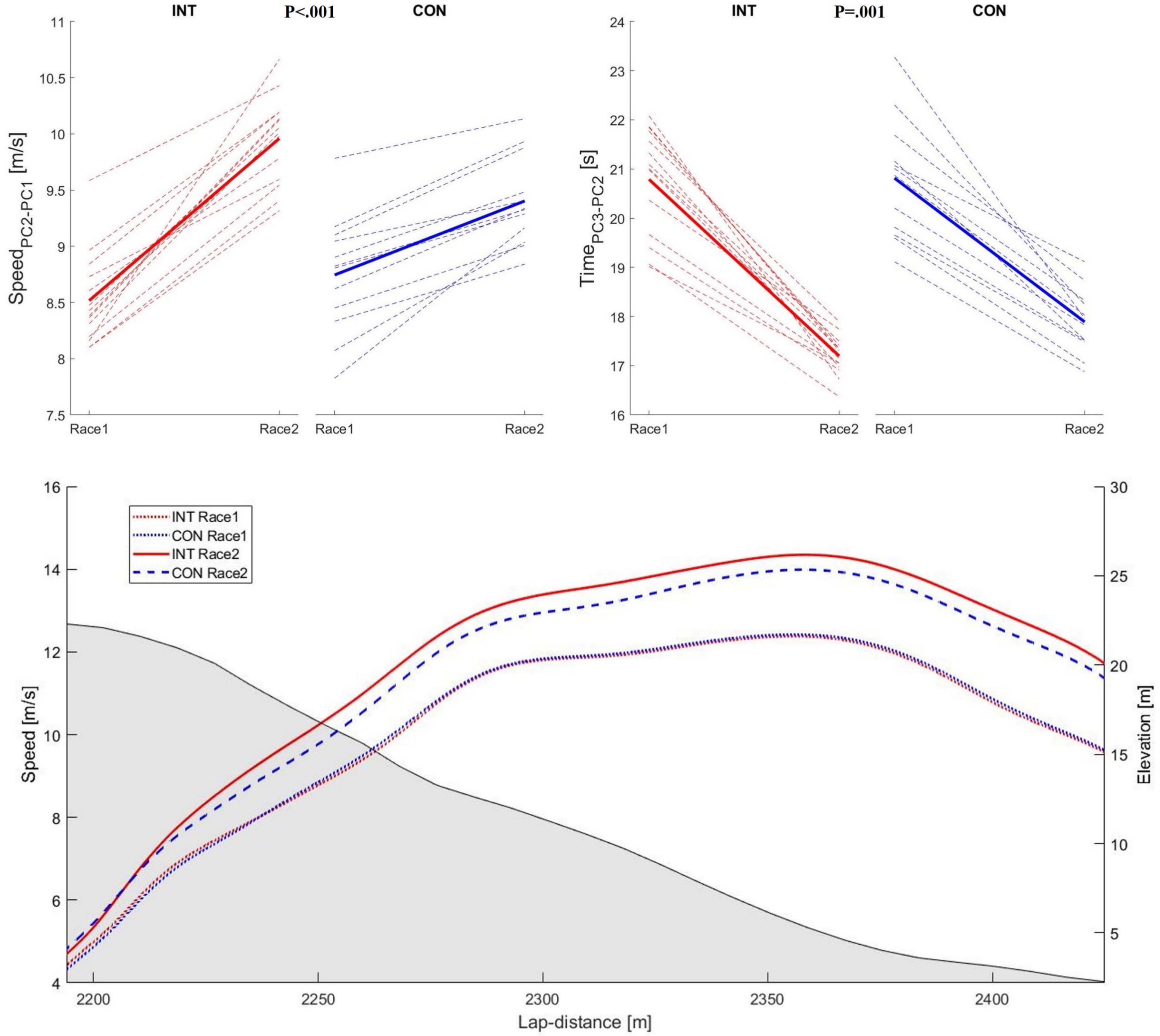

Figure 2 — Downhill segment 10. Upper graphs: Speed$_{PC2–PC1}$ and Time$_{PC2–PC1}$ (s) in Race1 and Race2 for the INT and the CON, individual values printed in dotted lines, and mean values in bold lines. *P* values for relative differences between groups are displayed. Lower graph: Continuous speed (m·s^{-1}; measured with GNSS) for Race1 and Race2 for INT and CON. CON indicates control group; INT, intervention; PC, photocell.

micropacing training session. This is likely explained by more active poling and leg kicks (measured by the total variance of the chest acceleration) leading to increased speed and reduced time in the subsequent downhill. This is in line with previous findings during a classical sprint competition, where instant speed during the acceleration phase over hilltops was related to the time spent in the subsequent downhill segment.[12]

The increased speed at the start of the downhill was not linked to the skiers' maximal aerobic power (VO_2peak in skating) or the 20-m speed tests, implying that the increase in performance occurred independently of these factors. However, the skiers with lower initial speed in the specific downhill segment during Race1 improved their speed more than the skiers with higher initial speed. In addition, the skiers with longer race time in Race1 improved overall race time more than faster skiers. Accordingly, individual strengths and weaknesses should likely provide the point of departure for further developing micropacing strategies. This is in line with the recent intervention study by Losnegard,[11] showing that XC skiers with a fast-start pacing pattern improved their performance by reducing the speed in the first uphill. However, there is a lack of studies comparing the costs and benefits of different micropacing strategies in XC skiing or similar endurance sports. More research is therefore required to understand this aspect of racing.

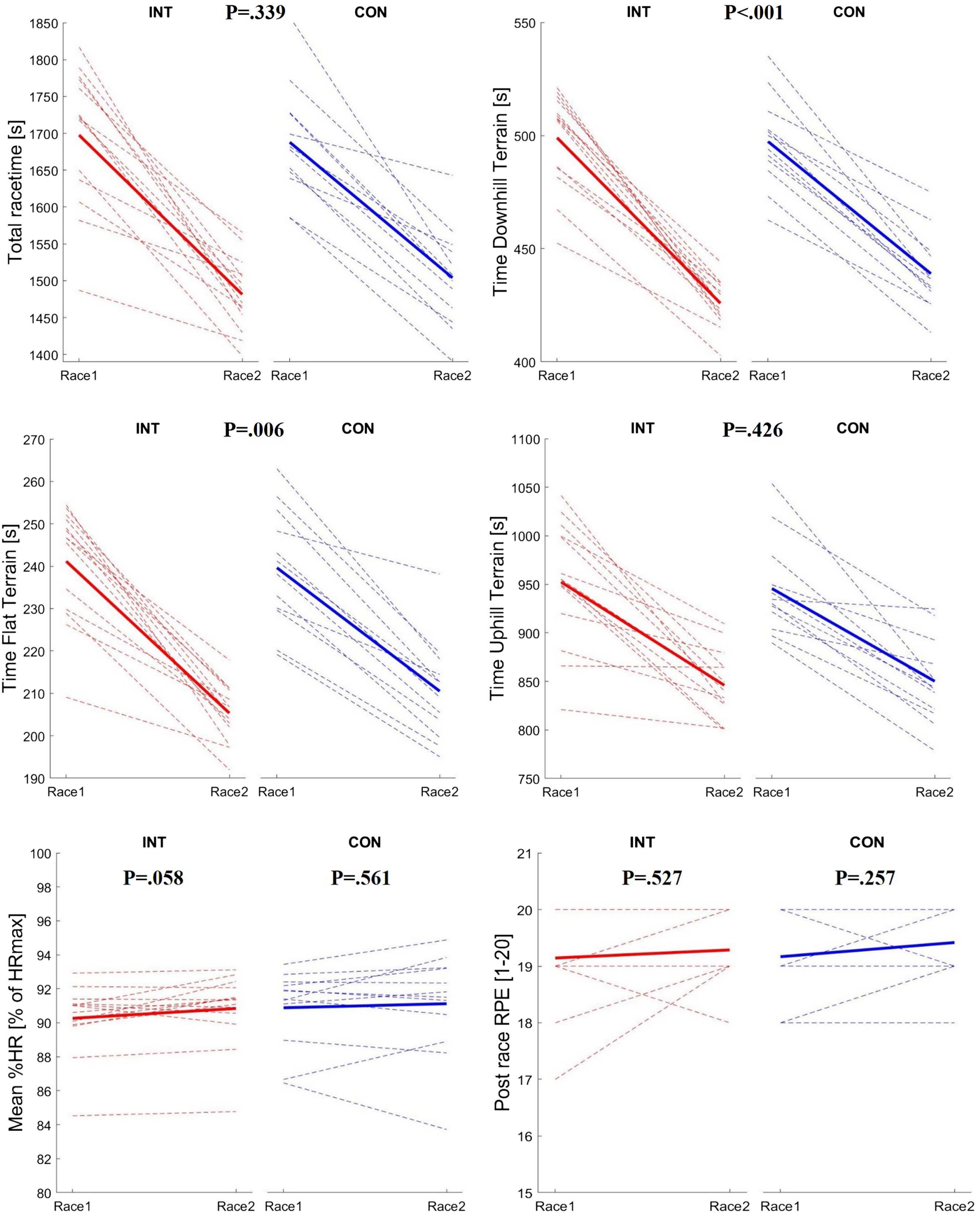

Figure 3 — Individual and mean values for Race1 and Race2 for the INT and the CON for total race time (s); overall time in downhill, flat, and uphill terrain; relative HR in % of maximal HR; and RPE. *P* values for relative improvement in total race time, overall time in downhill, flat and uphill terrain from Race1 to Race2 between groups, and *P* values for change in HR and RPE from Race1 to Race2 for both groups are displayed on the figure. CON indicates control group; HR, heart rate; INT, intervention group; RPE, rating of perceived exertion.

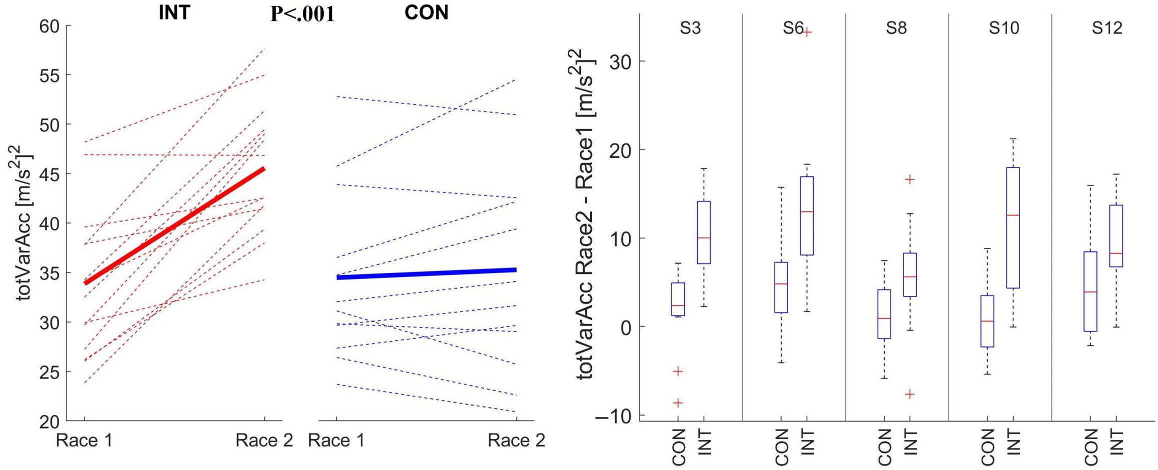

Figure 4 — The totVarAcc ($[\text{m}\cdot\text{s}^{-2}]^2$) on the hilltop of S10 for the INT and the CON for Race1 and Race2 (left graph), *P* value for relative difference between groups is displayed. Relative totVarAcc (%) on the hilltops for Race2 compared with Race1 for INT and CON for all downhill segments, observations that lie outside the interval defined by the box and outliers are marked with red crosses. (all $P < .001$) (right graph).

Table 1 Correlations (*R*) Between Improvement From Race1 to Race2 and Performance Indicators for the Intervention Group

	$\Delta\text{Speed}_{\text{PC2–PC1}}$, $\text{m}\cdot\text{s}^{-1}$		$\Delta\text{Time}_{\text{PC3–PC2}}$, s		ΔRaceTime, s		$\Delta\text{totVarAcc}_{\text{S10}}$, $(\text{m}\cdot\text{s}^{-2})^2$	
	R	*P*	*R*	*P*	*R*	*P*	*R*	*P*
VO_2peak skate, $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	.19	.553	–.32	.313	–.32	.319	.03	.902
Max speed flat, $\text{m}\cdot\text{s}^{-1}$	.06	.837	.08	.800	.04	.906	.26	.201
Max speed uphill, $\text{m}\cdot\text{s}^{-1}$	.08	.796	.13	.664	.16	.576	.01	.980
Race1: $\text{Speed}_{\text{PC2–PC1}}$, $\text{m}\cdot\text{s}^{-1}$	–.57	.035	–.68	.007	–.30	.290	.30	.144
Race1: $\text{Time}_{\text{PC3–PC2}}$, s	.27	.065	.93	.000	.66	.010	.26	.205
Race1: RaceTime, s	.33	.247	.86	.000	.86	<.001	.35	.082
StartTime, min after 1.start	–.33	.225	–.56	.039	–.65	.012	.22	.251
Intracorrelation								
$\Delta\text{Speed}_{\text{PC2–PC1}}$, $\text{m}\cdot\text{s}^{-1}$	NA	NA	.59	.026	.24	.405	.735	<.000
$\Delta\text{Time}_{\text{PC3–PC2}}$, s	.59	.026	NA	NA	.85	<.001	.50	.009
ΔRaceTime, s	.24	.405	.850	<.001	NA	NA	.54	.004
$\Delta\text{totVarAcc}_{\text{S10}}$, $(\text{m}\cdot\text{s}^{-2})^2$	.75	<.000	.50	.009	.54	.004	NA	NA

Abbreviations: ΔRaceTime, improvement in total race-time from Race1 to Race2; $\Delta\text{Speed}_{\text{PC2–PC1}}$, increased speed after the acceleration phase in downhill segment 10 from Race1 to Race2; $\Delta\text{Time}_{\text{PC3–PC2}}$, decrease in glide time in downhill segment 10 from Race1 to Race2; $\Delta\text{totVarAcc}_{\text{S10}}$, $(\text{m}\cdot\text{s}^{-2})^2$, increase in total variation of chest acceleration on hilltop from Race1 to Race2; PC, photocell.

Although the skiers received specific feedback and performed practical training only in 2 of the 5 downhill terrain segments, INT improved performance more than CON in 4 downhill segments during the competition. This led to significantly greater improvements in INT versus CON in overall downhill terrain. The lack of improvement in one of the downhills (S6) was likely due to this segment being relatively short and steep, which limits the amount of time possible to save time by employing this micropacing strategy. Overall, this indicates that the employed intervention was sufficient to adopt better micropacing strategies also in other downhills than those focused on during the practical training session.

No effects of the intervention on uphill or overall race performance were found. Since the skiers were instructed to keep the same pace in the uphill sections before and after the intervention, the lack of improvement in uphill sections was not surprising. Previous studies clearly show a higher portion of time spent skiing uphill than downhill and that uphill terrain is the most performance-differentiating terrain in XC skiing.[7–10] A possible explanation for the lack of improvement in overall race performance is that

Table 2 Time (s) in Segments and Overall Flat/Up/Down Terrain per Lap (Mean Value for the 3 Laps and SD for the INT and the CON for Race1 and Race2

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**Lap**	**Lap**	**Lap**	**Lap**
Segment	**Flat**	**Up**	**Down**	**Flat**	**Up**	**Down**	**Up**	**Down**	**Up**	**Down**	**Up**	**Down**	**Flat**	**Flat**	**Up**	**Down**	**All**
Race1																	
$\mathrm{Time}_{\mathrm{INT}}$, s	9.5	142.0	27.0	46.5	33.9	18.0	41.9	56.9	48.1	24.5	51.6	40.0	24.5	80.4	317.4	166.3	564.2
$\mathrm{Time}_{\mathrm{CON}}$, s	9.5	140.9	26.3	45.9	33.5	18.2	41.5	56.5	47.9	24.7	51.4	40.1	24.5	79.9	315.2	165.8	560.9
$\mathrm{Std}_{\mathrm{INT}}$, s	0.4	9.8	1.1	2.9	2.2	0.6	3.3	2.5	2.7	0.9	4.0	2.1	1.3	4.3	20.3	6.7	31.3
$\mathrm{Std}_{\mathrm{CON}}$, s	0.4	6.3	1.1	2.8	2.5	0.4	3.0	2.5	2.9	1.1	2.2	1.7	1.5	4.4	15.8	6.4	26.6
Race2																	
$\mathrm{Time}_{\mathrm{INT}}$, s	8.2	131.4	24.8	40.6	29.3	16.7	33.1	48.2	42.9	21.2	45.2	31.0	19.7	68.4	282.0	142.0	492.4
$\mathrm{Time}_{\mathrm{CON}}$, s	8.3	132.7	25.5	41.4	29.5	17.1	33.6	49.7	42.9	21.9	44.6	32.2	20.4	70.2	283.4	146.3	499.9
$\mathrm{Std}_{\mathrm{INT}}$, s	0.2	5.1	0.7	1.7	1.5	0.4	1.7	1.6	1.7	0.5	2.3	0.9	0.6	2.2	11.2	3.3	16.7
$\mathrm{Std}_{\mathrm{CON}}$, s	0.4	6.0	1.1	2.2	1.8	0.7	2.1	2.2	2.9	0.7	2.6	1.5	1.3	3.8	14.1	5.4	23.3
Time in segments, s, linear mixed model																	
$\Delta_{\mathrm{INT-CON}}$	−0.18	−2.08	−1.25	−1.36	−0.40	−0.29	−0.8	−1.69	−0.14	−0.55	0.50	−1.03	−0.62	−2.15	−3.01	−4.79	−9.97
Upper CI	−0.40	−5.78	−1.75	−2.34	−1.45	−0.59	−1.95	−2.68	−1.52	−0.9	−0.89	−1.84	−1.25	−3.67	−10.41	−7.12	−20.42
Lower CI	0.04	1.62	−0.76	−0.38	0.65	0.00	0.35	−0.70	1.25	−0.19	1.89	−0.22	0.02	−0.63	4.39	−2.47	0.48
P	.111	.271	<001	.006	.458	.053	.173	0.001	.846	.003	.480	.013	0.058	.006	.426	<001	.061
totVarAcc, $(\mathrm{m \cdot s^{-2}})^2$, linear mixed model																	
$\Delta_{\mathrm{INT-CON}}$			4.89			4.16		3.08		6.18		3.71					
Upper CI			3.43			2.01		1.24		4.48		2.07					
Lower CI			6.36			6.31		4.91		7,88		5.34					
P			<.000			<.000		<.001		<.000		<.000					

Abbreviations: $\Delta_{\mathrm{INT\text{-}CON}}$, difference in performance for INT compared with CON from Race1 to Race2; CI, confidence interval; CON, control group; INT, intervention group; totVarAcc, total variation of chest acceleration on hilltops. Note: The difference in performance (time in segments or acceleration intensity on hilltops) between INT compared with CON in Race1 to Race2 including *P* values and CIs are from a linear mixed model where skier id is random factor and lap and race day/group are fixed factors.

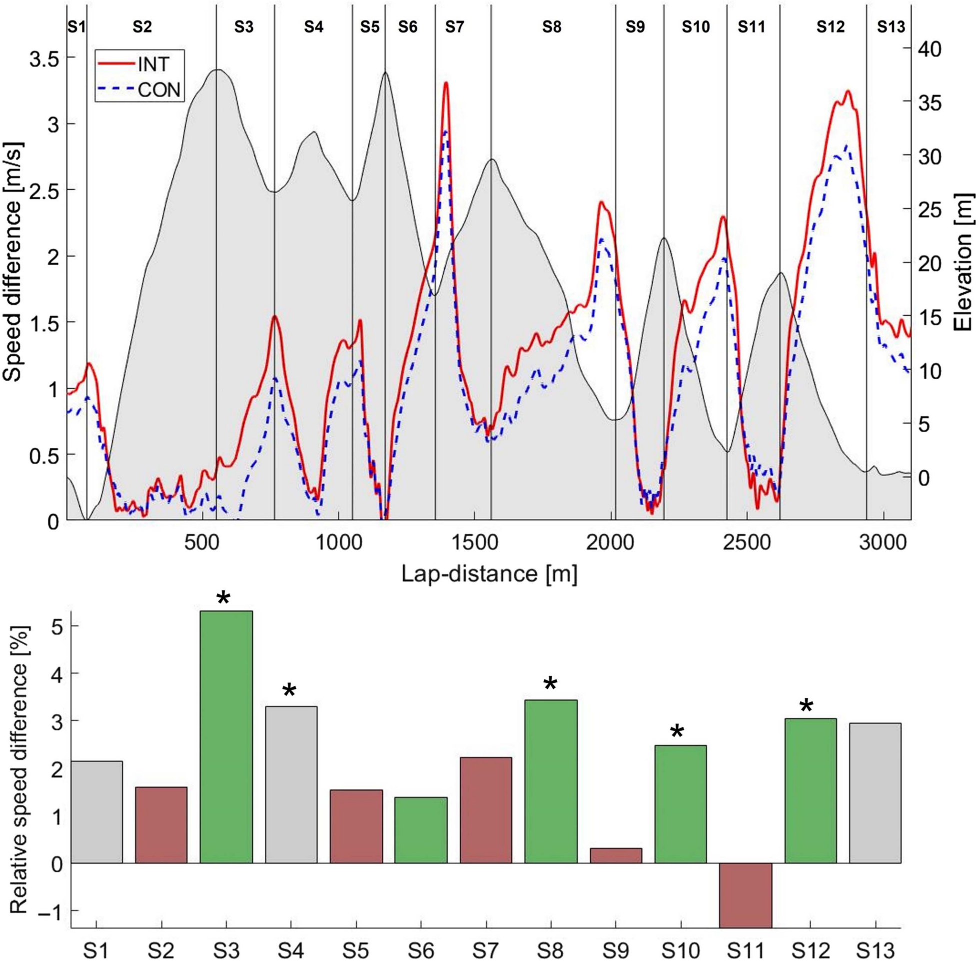

Figure 5 — Upper graph: Mean speed difference ($m \cdot s^{-1}$) and elevation (m) for Race2 compared with Race1 as a function of lap distance (m) for the INT and the CON. Lower graph: Relative improvement in speed for each segment for INT compared with CON in Race2 compared with Race1. *Significant difference in improvement between the groups ($P < .05$). CON indicates control group; INT, intervention group.

the individual performance differences from Race1 to Race2 in the uphill terrain have "masked" the improvements observed in the downhill sections in this relatively heterogeneous group of skiers. This is also supported by a recent investigation of micropacing strategies during a distance XC skiing competition, showing that skiers with shorter race times skied faster in specific parts of the uphills.[23] The lack of improvement in the overall performance could also be that some of the high-level skiers included in our study already were familiar with the micropacing strategy and therefore gained little time from the intervention. Lastly, although the study design (ie, balanced groups both according to performance and starting time) took into account some of the changes in snow and weather conditions, we cannot exclude that the nonlinear changes in the external conditions during the race days may have impacted the results.

Although the observed improvements in downhill terrain in INT did not significantly influence the overall competition performance, better downhill performance might be crucial when the margins between skiers are small.[12,24] In the current study, INT improved 14.6 s/2.9% in downhill and 6.5 s/2.7% in flat terrain compared with CON, corresponding to 1.0% and 0.4% of the total competition time, respectively. This improvement is greater than the smallest worthwhile improvement (defined as the required improvement in performance that could significantly influence the results), calculated to be 0.3% to 0.4%.[24] An interesting question is also whether a more extended intervention period, including several training sessions with feedback in different race courses can improve skiers micropacing strategy enough to influence the overall result in XC skiing.

Practical Applications

High-level XC skiers can reduce the time spent in downhill and flat terrain by implementing a terrain specific micropacing strategy using video- and sensor-based feedback in a time-efficient manner. The combination of a theoretical lecture, including video and speed analysis highlighting the potential to gain seconds, and objective feedback directly after each trial during a training session, seems to have created an effective learning process. Furthermore, this methodology can likely be used to develop better micropacing skills in other parts of the course or by focusing on technical aspects like the choice of subtechnique or regulation of cycle length and rate. Nevertheless, it is important that the coaches and skiers carefully analyze race courses and evaluate where there are the most seconds to gain from such strategies. Furthermore, the time spent training on this must also be weighed against improving other factors of importance for performance in XC skiing (eg, high aerobic power and efficient technique).

Conclusions

Targeted training combined with video- and sensor-based feedback led to a successful implementation of a terrain-specific micropacing strategy in XC skiing, which induced higher speed and reduced the time spent in downhill- and flat terrain sections compared with a control group. However, no change in overall performance was observed between the 2 groups of XC skiers.

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