Doctoral theses at NTNU, 2023:235

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Pacing strategy, race tactics, and the finish sprint

Doctoral thesis

NTNU
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Thesis for the Degree of Philosophiae Doctor
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ISBN 978-82-326-7170-0 (printed ver.)
ISBN 978-82-326-7169-4 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

Doctoral theses at NTNU, 2023:235

Printed by NTNU Grafisk senter

Hvordan vinne sprintlangrenn: Løpsstrategi, taktikk og sluttspurt

Bakgrunn: Selv om det ikke er undersøkt spesifikt i tidligere studier, er skiløpernes taktikk og evnen til å skape en høy hastighet i sluttspurten anerkjente prestasjonsavgjørende faktorer i sprintlangrenn. Det overordnede målet med avhandlingen var derfor å undersøke forklaringsvariabler for prestasjon i heat og evnen til sluttspurt i konkurranser på snø.

Funn: I *studie I* ble hastighet og kinematikk under 4 simulerte prologer med konservativ (kontrollert start) og positiv (hard start) løpsstrategier i begge stilarter i randomisert rekkefølge undersøkt hos 12 mannlige skiløpere på nasjonalt nivå. Omtrent 85% av maksimal hastighet ble oppnådd i sluttspurten, hvor maksimal hastighet og prosentvis utnyttelse av maksimal hastighet bidro i like stor grad til å forklare sluttspurthastigheten under de fire simulerte prologene, både i klassisk og skøyting, og var uavhengig av løpsstrategi. Av den grunn bør derfor skiløpere i sprintlangrenn utvikle begge disse kapasitetene samtidig og bruke tekniske strategier der en høy syklushastighet kan opprettholdes når man blir utmattet. Forskjellen i kinematiske mønstre mellom hva som ble oppnådd i den maksimale hastighetstesten i uthvilt tilstand og sluttspurten i prologene var 11-22% redusert syklushastighet i begge stilarter uten endringer i sykluslengde. I klassisk stil var spurthastigheten 3,6% raskere med den konservative løpsstrategien sammenlignet med den positive løpsstrategien, og denne forskjellen ble forklart av høyere syklushastighet. Til sammenligning var den prosentvise forskjellen i sluttspurthastighet mellom strategier i skøyteteknikk den samme, men denne forskjellen nådde ikke statistisk signifikans. I *studie II* ble hastighet, posisjonering og kinematikk i heatene i en internasjonal konkurranse i sprintlangrenn i klassisk stil undersøkt hos 30 mannlige skiløpere på nasjonalt- til verdensklassenivå. De viktigste prestasjonsavgjørende faktorene i heatene var en topprangert plassering da man nærmet seg segmentet med den siste oppoverbakken i kombinasjon med høyere hastighet i diagonal ved å bruke lengre sykluslengde og høyere syklushastighet. I *studie III* ble betydningen av posisjonering for prestasjon i 16 konkurranser i sprintlangrenn og dens konsistent over gjentatte konkurranser i samme konkurranseløype undersøkt hos mannlige og kvinnelige skiløpere på elite- til verdensklassenivå. Her fant vi en gradvis større betydning underveis i løypen av å være posisjonert i tet i heatene i internasjonalt sprintlangrenn blant menn og kvinner, hvor mesteparten av variasjonen i prestasjon ble avgjort før starten av sluttspurten i klassisk- og skøyteteknikk. Sluttplasseringen for begge kjønn avgjort på et tidligere stadium i skøyting sammenlignet med klassisk, noe som sannsynligvis forklares av større muligheter for posisjonering under heatene i klassisk enn skøyting. Det var ingen signifikante forskjeller i passeringer mellom sesonger for konkurranser i samme løype med sammenlignbare ytre forhold.

Oppsummering: Denne avhandlingen bidrar til ny kunnskap om løpsstrategi, taktikk, og evnen til sluttspurt i sprintlangrenn. Den praktiske betydningen av funnene er at slike analyser som vist i avhandlingen kan hjelpe skiløpere med å optimalisere sine individuelle løpsstrategier både under trening og konkurranser.

“When you have the *why* figured out, then you can do any *how*.”

- JEFF GUM, U.S. Navy SEALs

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LIST OF PUBLICATIONS

Study I**:** Haugnes, P., Torvik, PØ., Ettema, G., Kocbach J., & Sandbakk, Ø. (2018). The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition. *International journal of Sports Physiology and Performance*. doi:10.1123/ijspp.2018-0507

Study II**:** Haugnes, P., Kocbach, J., Talsnes, R., Noordhof D., Ettema, G., & Sandbakk, Ø. (2022). The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. *PLoS One*. doi: 10.1371/journal.pone.0278552

Study III: Haugnes, P., Kocbach, J., Noordhof D., Talsnes, R., Ettema, G., & Sandbakk, Ø. (2023). The influence of tactical positioning on performance in sprint cross-country skiing. *PLoS One.* doi: 10.1371/journal.pone.0287717

ABSTRACT

Sprint cross-country (XC) skiing involves whole-body exercise on varying terrain using different sub-techniques of the classical and skating styles. The competition involves one to four ~3 min races, where the qualifying sprint time-trial (STT) is followed by three subsequent heats, in which six skiers compete and the top-two qualify for the next round along with the two fastest remaining skiers. Although not examined specifically in previous research, the skiers race tactics, and the ability to generate a high finish sprint speed are well recognized determinants of sprint XC skiing performance. The overall objective of this thesis was to explore race tactics in sprint XC skiing by investigating within-race determinants of heat performance and finish sprint ability in on-snow competitions.

In *study I*, speed and kinematics during four simulated STTs performed with conservative (controlled start) and positive (hard start) pacing strategies in both styles in a randomized order was investigated in twelve male national-level sprint skiers. Approximately 85% of maximal speed (V_{max}) was obtained in the finish sprint, with V_{max} and $\%V_{max}$ contributing similarly (R^2 = 51-78%) to explain the overall variance in finish sprint speed. The differences in kinematic patterns between the V_{max} bout and the STT finish sprint were 11-22% reduced cycle rate (CR) in both styles without any changes in cycle length (CL). In the classical style, the finish sprint speed was 3.6% faster with the conservative pacing compared with the positive pacing strategy ($P < .001$), and this difference was explained by higher CR. In comparison, the percentage difference in finish sprint speed between strategies in the skating style was the same, but this difference did not reach statistical significance. In *study II*, speed, positioning, and kinematics in the heats of an international sprint XC skiing competition in the classical style was investigated in thirty male national to world-class level sprint skiers. The top-two finishers in each heat were ~4% slower in the heats compared to the STT ($P < .001$). On average, the skiers performed 10 overtakings per 100 m from the start to the last uphill segment, but only ~3 overtakings per 100 m in the last two segments in each heat. As much as 94% of the top-two finishing skiers positioned themselves at top-two before approaching the final uphill, in which the top-four finishers were generally faster than those ranked 5-6. Here, top-four employed 5.3% longer CL and 3.4% higher CR in the diagonal (DIA) sub-technique than skiers ranked 5-6. A relatively similar technique distribution across skiers was observed within and between heats. In *study III*, the influence of positioning on performance in 16 sprint XC skiing competitions and its consistency over repeated competitions on the same racecourse was

investigated in male and female elite to world-class level sprint skiers. The STT rank correlated positively with the final rank for seven male (ρ=.54-.82, $P < .01$) and eight female (ρ = .40-.80, $P < .05$) competitions, while the STT rank and final rank did not correlate significantly in one of the classical competitions for men (P = .23). The strength of the correlation coefficients between intermediate ranks and final ranks during the heats increased gradually from the first to the last checkpoint among both sexes in the classical style (τ = ~0.24 to ~0.70) and in the skating style (τ = ~0.20 to ~0.84). In both sexes and styles, the heat winners positioned themselves gradually further towards the front of the heat with ~94% being ranked top-two at the last checkpoint before the finish sprint. For both sexes, an average of ~20 and ~16 overtakings were observed in each heat for the classical and skating style, respectively. There was a significant sex-difference in the number of overtakings in one out of the 16 competitions ($P < .004$), but no differences across seasons for competitions held on the same racecourse (P = .051-.796).

This thesis provides new knowledge on pacing strategy, race tactics, and the finish sprint ability in sprint XC skiing. In *study I*, the V_{max} ability and the $\%V_{max}$ contributed similarly to explain the finish sprint speed during the four simulated STTs, both in the classical and skating styles, and were independent of pacing strategy. Thus, sprint XC skiers should therefore concurrently develop both these capacities and employ technical strategies where a high CR can be sustained when fatigue occurs. In *study II*, the main performance-determining factors in the heats of the international sprint XC skiing competition were a top-two position when approaching the final uphill segment in combination with higher speed by utilising longer CL and higher CR in DIA. In *study III*, we found that the importance of being positioned at the front in the heats of international XC sprint skiing among men and women became more important the further into the racecourse, in which the majority of performance-variance was decided before the start of the finish sprint in both styles. The final rank for both sexes was decided at an earlier stage in the skating style compared to the classical style, which is likely explained by greater possibilities for positioning during the heats in the classical style. There were no significant differences in overtakings between seasons for competitions organized on the same type of racecourse with comparable conditions. Overall, this thesis shows the importance of finish sprint ability and positioning for performance in sprint XC skiing, with the number of overtakings being relatively consistent between competitions performed on the same racecourse. The practical implications are that an accurate racecourse analysis may help skiers to optimize their race-individual race-strategies in sprint XC skiing.

SUMMARY IN NORWEGIAN

Sprintlangrenn involverer trening av hele kroppen i variert terreng ved å bruke forskjellige delteknikker i klassisk- og skøyteteknikk. Konkurransen i sprintlangrenn involverer et til fire ~3-min løp, hvor den individuelle prologen (STT) er etterfulgt av tre påfølgende heat, der seks skiløpere konkurrerer mot hverandre ved å bruke et utslagssystem der de to første utøverne i hvert heat kvalifiserer seg for de neste rundene sammen med de to raskeste gjenværende skiløperne. Selv om det ikke er undersøkt spesifikt i tidligere studier, er skiløpernes løpstaktikk og evnen til å skape en høy hastighet i spurten anerkjente prestasjonsavgjørende faktorer i sprintlangrenn. Det overordnede målet med denne avhandlingen var å utforske løpstaktikk i sprintlangrenn ved å undersøke forklaringsvariabler for prestasjon innen hvert heat og evnen til spurt i konkurranser på snø.

I *studie I* ble hastighet og kinematikk under fire simulerte STT med konservativ (kontrollert start) og positiv (hard start) løpsstrategier i begge stilarter i randomisert rekkefølge undersøkt hos tolv mannlige skiløpere på nasjonalt nivå. Omtrent 85% av maksimal hastighet (V_{max}) ble oppnådd i spurten, hvor V_{max} og $\%V_{max}$ bidro på samme måte (R^2 = 51-78%) til å forklare variasjonen i spurthastigheten. Forskjellen i kinematiske mønstre mellom V_{max} testen og spurten i STT var 11-22% redusert syklushastighet i begge stilarter uten endringer i sykluslengde. I klassisk stil var spurthastigheten 3,6% raskere med den konservative løpsstrategien sammenlignet med den positive løpsstrategien ($P < .001$), og denne forskjellen ble forklart av høyere syklushastighet. Til sammenligning var den prosentvise forskjellen i sluttspurthastighet mellom strategier i skøyteteknikk den samme, men denne forskjellen nådde ikke statistisk signifikans. I *studie II* ble hastighet, posisjonering og kinematikk i heatene i en internasjonal konkurranse i sprintlangrenn i klassisk stil undersøkt hos 30 mannlige skiløpere på nasjonalt- til verdensklassenivå. De to raskeste i hvert heat var ~4% tregere i heatene sammenlignet med STT ($P < .001$). I gjennomsnitt utførte skiløperne 10 passeringer per 100 m fra start til segmentet med den siste oppoverbakken, men kun ~3 passeringer per 100 m i de to siste segmentene i hvert heat. Så mye som 94% av de to beste skiløperne plasserte seg på de to fremste posisjonene i heatet før de nærmet seg den siste oppoverbakken, der de fire beste skiløperne generelt var raskere enn de som var rangert 5-6 i heatene. Her brukte de fire beste skiløperne 5,3% lengre sykluslengder og 3,4% høyere syklushastigheter i delteknikken diagonal (DIA) enn skiløperne rangert 5-6. En relativ lik teknikkdistribusjon ble observert i og mellom hvert heat. I *studie III* ble påvirkningen av posisjonering for prestasjon i 16

konkurranser i sprintlangrenn og dens konsistent over gjentatte konkurranser i samme konkurranseløype undersøkt hos mannlige og kvinnelige skiløpere på elite- til verdensklassenivå. Rangering av den individuelle STT korrelerte positivt med sluttplasseringen for syv mannlige (ρ = .54-.82, $P < .01$) og åtte kvinnelige (ρ = .40-.80, $P < .05$) konkurranser, mens rangeringen av STT og sluttplasseringen korrelerte ikke signifikant for en av konkurransene i klassisk for menn ($P = .23$). Styrken på korrelasjonskoeffisientene mellom sjekkpunkt i konkurranseløypa og siste sjekkpunkt i heatene økte gradvis fra første til siste sjekkpunkt for begge kjønn i klassisk (τ = ~0,24 til ~0,70) og i skøyting (τ = ~0,20 til ~0,84). I begge kjønn og stilarter posisjonerte vinnerne av hvert heat seg gradvis mot teten av heatet, hvor ~94% ble rangert som de to første plasseringene på siste sjekkpunkt før spurten. For begge kjønn ble det i gjennomsnitt observert ~20 og ~16 passeringer i hvert heat for henholdsvis klassisk og skøyting. Det var en signifikant kjønnsforskjell i antall passeringer i én av de 16 konkurransene ($P < .004$), men ingen forskjeller mellom sesonger for konkurranser arrangert i samme løype (P = .051-796).

Denne avhandlingen bidrar til ny kunnskap om løpsstrategi, løpstaktikk, og evnen til spurt i sprintlangrenn. I *studie I* bidro V_{max} og $\%V_{max}$ i like stor grad til å forklare spurthastigheten under de fire simulerte prologene, både i klassisk og skøyting, uavhengig av løpsstrategi. Av den grunn bør derfor skiløpere i sprintlangrenn utvikle begge disse kapasitetene samtidig og bruke tekniske strategier der en høy syklushastighet kan opprettholdes når man blir utmattet. I *studie II* var de viktigste prestasjonsavgjørende faktorene i heatene i den internasjonale konkurransen i klassisk stil en topprangert plassering når man nærmet seg segmentet med den siste oppoverbakken i kombinasjon med høyere hastighet i DIA ved å bruke lengre sykluslengde og høyere syklushastighet. I *studie III* fant vi en gradvis større betydning underveis i løypen av å være posisjonert i tet i heatene i internasjonalt sprintlangrenn blant menn og kvinner, hvor mesteparten av variasjonen i prestasjon ble avgjort før starten av spurten i begge stilarter. Sluttplasseringen for begge kjønn ble avgjort på et tidligere stadium i skøyting sammenlignet med klassisk, noe som sannsynligvis kan forklares med større muligheter for posisjonering i heatene i klassisk enn skøyting. Det var ingen signifikante forskjeller i passeringer mellom sesonger for konkurranser arrangert i samme løype med sammenlignbare ytre forhold. Oppsummert viser denne avhandlingen viktigheten av spurt og posisjonering for prestasjon i sprintlangrenn, hvor antall passeringer var relativt lik for konkurranser arrangert i samme konkurranseløyper. Den praktiske betydningen av funnene er at konkurranseanalyser kan hjelpe skiløpere med å optimalisere sine individuelle løpsstrategier i sprintlangrenn.

ACKNOWLEDGEMENTS

Ever since I read the book “The first crossing of Greenland” by the Norwegian explorer and scientist Dr. Fridtjof Nansen, my goal has been to earn a doctoral degree and to reach the North Pole on skis. Now I am halfway there. Dr. Fridtjof Nansen, wrote his doctoral thesis in Neurobiology and successfully defended it on the 28th of April 1888. No less than some days later, his expedition sat sail for Greenland’s east coast with the motto “Death or the west coast of Greenland.” My academic voyage will follow in the same track since I am now working on a research project with adventurer Rune Gjeldnes and my main supervisor, Prof. Øyvind B. Sandbakk, who has made this possible. You have been a living North Star for me in your guidance. Thank you.

Speaking of ice, my co-supervisors Prof. Gertjan Ettema and Dr. Dionne Noordhof, from the Netherlands, have truly set the standard for scientific work. My hope is one day to be able to see and understand the scientific discoveries as they do. One person who really has tried to teach me from the beginning has been Dr. Jan Kocbach, who is a pioneer in the development and use of sensor technology in sports science. What haven’t you taught me?

As I write my thanks to all those who have helped me, there are two wartime speeches by Winston Churchill in 1940 that cross my mind: “I have nothing to offer but blood, toil, tears and sweat”, and “Never was so much owed by so many to so few.” Up to the present time, this thesis has been like an actual competition in sprint cross-country skiing, with its challenges and joys. I am proud and honoured to have worked with skiers, coaches, and researchers, from the far east to the high north. Thank you all for your team effort. I would also like to thank all the people at NTNU Centre for Elite Sports Research, Olympiatoppen Mid-Norway, Nord University in Meråker, SINTEF, and NTNU Faculty of Medicine and Health Sciences. None mentioned, none forgotten.

Who are we without family and friends? I am so glad you are on my team. Thank you for all the time we have been together and all the time we have been without each other during this period. I am beyond grateful.

Lotte, thank you for your love and support!

ABBREVIATIONS

Bla	Blood lactate concentration
CL	Cycle length
CR	Cycle rate
CT	Cycle time
DIA	Diagonal stride
DK	Double poling with a kick
DP	Double poling
F	Final
FIS	International Ski and Snowboard Federation
G3	Double dance
GNSS	Global Navigation Satellite Systems
GPS	Global positioning system
HR	Heart rate
HR_{max}	Maximal heart rate
IMU	Inertial measurement unit
OTHER	Other techniques including tucking and turning
QF	Quarterfinal
RPE	Rating of perceived exertion
SF	Semi-final
STT	Sprint time-trial
TCK	Tuck
TRN	Turning techniques
V_{max}	Maximal speed
$\%V_{max}$	Percentage of maximal speed
$\dot{V}O_2max$	Maximal oxygen uptake
XC skiing	Cross-country skiing

INTRODUCTION

Sprint cross-country skiing characteristics

Sprint cross-country (XC) skiing is regarded as a highly demanding endurance sport, involving combined upper- and lower-body exertion of varying intensity where the skiers employ different sub-techniques (gears) of the classical and skating styles, in which they continuously change between gears and adapt according to the speed (ranging from 5 to 70 km/h), terrain (fluctuates between -20 to +20 percent gradients), and external conditions (i.e., altitude, friction, temperature, and wind).[1-3] The sprint XC competition involves one to four ~3-minute races performed on varying terrain (1.0-1.8-km) separated by ~15-60 min breaks, where the ability to recover in between heats is important for performance in the subsequent heats. The sprint time-trial (STT) race is followed by three subsequent knockout heats [(five quarterfinals (QF), two semi-finals (SF), and one final (F)], in which six competitors compete head-to-head for the first two ranks (top-two) that qualify for the next heats along with the two fastest remaining skiers ('lucky losers'). Consequently, to perform in sprint XC skiing and finish as either top-two or lucky loser in the heats, the skiers need to pace and position themselves as the first ranks, and at the same time recover to perform well in the subsequent heat. Hence, maximal oxygen uptake ($\dot{V}O_2max$), fractional utilization of $\dot{V}O_2max$, skiing efficiency/economy, technique expertise, and the ability to generate a high finish sprint, as well as race tactics (including positioning) are recognized determinants of sprint XC skiing performance.[4-13] However, while sprint XC skiing has been analysed in detail in the laboratory the recent years, we have limited knowledge about pacing strategy, race tactics, and the finish sprint ability in actual sprint XC competitions outdoors on snow.

Pacing strategy, race tactics, and finish sprint ability

The sprint XC skiers' pacing strategy, that is the individual's distribution of effort, in the STT is regulated according to the skiers' own racing template where the aim is to optimise the overall time in the race based on the given external conditions and the individual skier's strength and weaknesses. The pacing strategy in the STT is generally positive, meaning that the speed is reduced on comparable terrain segments throughout the racecourse with increased generation of external work rate in the uphill sections and reduced effort downhills. Importantly, the uphill sections are the terrain that separates the best from the rest, and the skiers' time distribution spent on uphill, flat, and downhill sections contribute in that order to the overall performance in the STT.[1,6,14-21] Another important point to take into considerations when the skiers compete in the subsequent heats, is that the skiers' aim is not necessarily to ski as fast as possible as in the STT, but to finish primarily as top-two in the heats, and thereafter recover rapidly in between heats. Those who perform in the STT will in many cases also perform in the subsequent heats, as shown with the moderate to large correlations between STT rank and final rank previously reported,[10] where Spencer et al.[10] found stronger correlations for men than for women, and this difference was clearly greater in the skating style. The individual's speed, positioning, and sub-technique selection in the heats before entering the finish sprint leads to various degrees of fatigue, which results in reduced physiological, biomechanical, and/or physiological capacities.[22,23] How fatigued the skiers are in the finish sprint depends on several factors additional to metabolic energy regulation, such as the other skiers' strategies. The best skiers in sprint XC skiing can control the speed in the race, meaning that some heats are characterized by fast speed from the start, whereas other heats have more elements of tactical skiing where the skiers take advantage of drafting behind competitors, and avoidance of accidents. Hence, all these factors may influence the skiers' fatigue and sprint ability when reaching the finish sprint.[24-30] The ability to generate a high speed when sprinting in the finish sprint is determined by the combination of having a high maximal speed (V_{max}) and the ability to utilize a high fraction of V_{max} (%V_{max}). Furthermore, the main techniques in the classical and skating styles in sprint XC skiing, particularly in the end of the finish sprint, is double poling (DP) in the classical style,[31] where all propulsive forces are produced through the poles,[32] and G3 in the skating style, which is used in the same terrain types as DP. Here, the propulsion is generated concurrently by the leg push-off and the DP movement,[33] which makes G3 skating naturally much faster than DP.[34] Currently, there is not known whether there are differences between the %V_{max} utilized in a finish sprint between these styles and how the coinciding kinematics may change. To reach V_{max} in both styles, the skiers are required to ski with a high cycle rate (CR) and a concurrently long cycle length (CL),[35,36] while the ability to utilize a high %V_{max} is influenced by the individual's levels of fatigue. As has been noted, this plays a big role at the end of the race, where you are both physically and mentally exhausted from racing, and you need to ski as fast as possible according to your maximum capacity to perform in the finish sprint.[14] The reduction in finish sprint speed in previous simulated sprint XC competitions on skis and roller skis has been associated with changes in muscle activity patterns and kinematic adaptions, such as reduced CR, lower pole force, as well as decreased muscle activation.[24-28,30,37] At present time, how V_{max} and %V_{max} contributes to the finish sprint speed using both styles or to what extent CL and/or CR contribute to finish sprint speed have not yet been studied. Also, whether the same findings regarding fatigue in the finish sprint occur in actual sprint XC competitions outdoors in both styles, and to what extent kinematic pattern and pacing strategy would influence the finish sprint have not yet been investigated.

The skiers' race tactics in the heats, regarded as an important determinant of performance in sprint XC skiing, has only been examined in three recent studies.[38-40] In a simulated competition in the skating style, Andersson et al.[39] found that most heat winners (61%) were leading already after the initial start of their respective heats, and that the correlations between intermediate rankings and the final rank ranged between 0.51-0.84, and the strength increased towards the finish sprint. Andersson et al.[39] also classified sub-techniques and the corresponding kinematic patterns by using video recordings. However, the analysed cycles were collected from short uphill sections spanning 25-40 m and in the finish sprint, which reduces the generalizability of their results. Marsland et al.,[38,40] identified individual differences for female skiers in pacing strategy, sub-technique selection, and related kinematic pattern over an entire racecourse of a classical sprint XC skiing race. Unfortunately, only six out of twelve skiers were analysed in the SFs and F since there were too few competitors for the QFs to be held. Since the period investigated by Spencer et al.,[10] Andersson et al.,[39] and Marsland et al.,[38,40] sprint XC skiing has evolved, where for example more skiers now are specialised in sprint XC skiing and both sexes more often competing on the same racecourse. Consequently, the influence of race tactics on performance in the heats of an actual sprint XC skiing competition nowadays is not fully explored. Accordingly, there is a need for an improved understanding and more updated information related to positioning, overtakings, sub-technique selection, and the related cycle characteristics in both styles for both men and women. In this context, knowledge about the consistency of the number and location of overtakings, when a competition is repeated on the same racecourse with comparable conditions is of interest for understanding the repeatability of the skier's race strategies. Importantly, this type of knowledge has practical relevance for subsequent racecourse preparations and training. The use of wearable sensor technology combined with video analysis of race tactics have the potential of full-course analyses, which can provide up-to-date scientific insight on the demands of sprint XC skiing.[1,2,21,38,40-54]

Aims

The primary objective of this thesis was therefore to explore race tactics in sprint XC skiing by investigating within-race determinants of heat performance and finish sprint ability in on-snow competitions. This was addressed in detail through the following three specific aims:

1) ***Study I***

- Aim: To investigate the contribution from maximal speed (V_{max}) and percentage of maximal speed (%V_{max}) to the finish sprint speed obtained in a XC sprint competition in the classical and skating style, as well as the coinciding changes in kinematic patterns and the effect of pacing strategy on the %V_{max}.
- Approach: Speed during the simulated 1.4-km sprint time-trials (STT) was tracked with a global navigation satellite system (GNSS) with integrated barometry and accompanying heart rate monitor. V_{max} and final sprint speed during the same section was monitored by photocells and video.

2) ***Study II***

- Aim: To examine the association of race tactics for performance in the heats of an international sprint XC skiing competition in the classical style.
- Approach: An integrated GNSS/IMU system was used to determine speed, sub-technique distribution, and kinematics during an international sprint XC skiing competition. Positioning was analysed using the publicly available television broadcast of the competition.

3) ***Study III***

- Aim: To examine the association of positioning on performance in the heats of sprint XC skiing competitions among men and women and its consistency over repeated competitions on the same racecourse.
- Approach: Video analysis of positioning and incidents were obtained by publicly available television broadcast of 16 competitions, where the racecourses were separated into 5 segments using 5 checkpoints based on terrain topography.

METHODS

Participants

As defined by Mckay et al.,[55] the 12 male XC skiers in *study I* (age: 21±2 y, body height: 183±4 cm, body mass: 78±7 kg, $\dot{V}O_2max$: 71±4 mL·min-1·kg^{-1}, training: 619±100 h y^{-1}) ranged from Tier 3 (National Level) to Tier 4 (Elite/International Level). The 30 male XC skiers in *study II* (age: 24±3 y, FIS sprint points: 61±27) ranged from Tier 3 to Tier 5 (World-Class Level). The 30 male and 30 female XC skiers in *study III* (see Table 5) within each competition ranged from Tier 4 (Elite/International Level) to Tier 5. All skiers in *studies I-II* were fully informed and signed written informed consent prior to participating and the protocols were preapproved by the Norwegian Center for Research Data and performed according to the Declaration of Helsinki. All data in *study III* were in the public domain and no written consent from the skiers nor ethical approval was sought.

General approach to the problem

The simulated STTs using both styles in *study I* was held in Norway in 2018 in the end of the competitive season (mid-April). Here, we tracked speed with a GNSS with integrated barometry and accompanying HR monitor, and the V_{max} section was monitored by photocells and video. The classical sprint XC skiing competition in *study II* was held in Norway in 2017 at the start of the competitive season (mid-November). An integrated GNSS/IMU system was used to determine position, sub-technique distribution and kinematics. The two repeated competitions at four different venues (two in the classical and two in the skating style) in *study III* were performed between 2017 and 2020. Positioning in *studies II-III* was analysed using the publicly available television broadcast of the races.

Instruments and materials

In *study I,* a running $\dot{V}O_2max$ test was performed on a 2.5 x 0.7-m motor-driven treadmill (RL 2500E, Rodby, Södertalje, Sweden) (see Fig 1) according to standardized procedures published previously.[56] Body mass and height were measured with an electronic body mass scale (Seca model nr. 708, Seca GmbH & Co, Hamburg, Germany) and a stadiometer (Holtain Ltd., Crosswell, UK). Blood lactate concentration (BLa) was analysed using a Biosen 5140 (EKF diagnostic GmbH, Magdeburg, Germany) analyzer. Gas exchange values were measured by open-circuit indirect calorimetry with an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Rating of perceived exertion (RPE) was recorded using the 6-to-20-point Borg Scale.[57] The maximal heart rate (HR_{max}) test was tested in an uphill test outdoors described previously.[58]

In *studies I-II*, all skiers performed self-selected warm-up according to their own individual program. The ski equipment was optimised for the specific athlete's racing preferences, including poles, boots, and skis. All ski-base preparations, including grinds, structure, and waxing, were optimised for the snow conditions. Each skier in *study I* wore the same GNSS sensor device, Garmin Forerunner 920XT (Garmin Ltd., Olathe, KS, USA) (see Fig 2), during the STTs, which collected position and heart rate (HR) data at a sampling rate of 1 Hz. We ensured GPS fixing, minimized inaccuracies, and determined course profiles, as previously described by Sandbakk et al.[59] The time each skier spent in a section was calculated based on virtual split times. Speed for each section was calculated by dividing the length of a section by the time elapsed within that section.

Fig 1. Illustration of the Rodby treadmill RL2500E used in the running VO_{2max} in *study I*.

Furthermore, BLa of 5-µL samples were analysed by using a Lactate Pro LT-1710t kit (Arkray Inc., Kyoto, Japan) (see Fig 2), HR was measured with a Garmin Forerunner 920XT (Garmin Ltd., Olathe, KS, USA) (see Fig 2) at a sampling rate of 1 Hz, and RPE was recorded using the 6-to-20-point Borg Scale.[57] The speed, position, and movement data in *study II* was tracked with an integrated sensor device, Optimeye S5, (Catapult Sports, Melbourne, Australia) (see Fig 2) with a sampling frequency of 10 Hz for the GNSS-data and 100-Hz for the IMU data. The sensor device has been validated for position, speed, and time analysis in XC skiing against a geodetic, multi-frequency receiver by Gløersen et al.,[60] which ensured that the sensor was able to detect differences reliably. We found the error for measured time vs. the official time in the competition in *study II* to be 0.05 ± 0.18 seconds. The racecourse in *study II* was measured by Matthias Felix Gilgien and his colleagues at the Norwegian School of Sport Sciences, which used a high-end differential, multi-frequency and multi-GNSS receiver (Alpha-G3T, Javad, San Jose, CA, USA) that provided a valid racecourse and elevation profile. V_{max} in *study I* was calculated based on time from two sets of photocells with 1000 Hz resolution (TC-Timer; Brower Timing Systems, Draper, UT, USA) (see Fig 2) placed at start and finish of the V_{max} section, 20 cm above the ground, and with 300-cm transmitter-reflector spacing. Official competition results in *study III*, including skiing times, was downloaded from the publicly available FIS online database (www.fis-ski.com). In *study I*, a panning 50-Hz Sony video camera (Sony Handycam HDR-PJ620, Sony Inc., Tokyo, Japan) (see Fig 2) monitored the skiers in the final 80-m finish sprint (V_{max} section) for 6 consecutive cycles to determine CR and CL. Video was analysed using an open-license motion-analysis software Kinovea version 0.8.15 for Windows (Free software Foundation Inc., Boston, MA, USA).

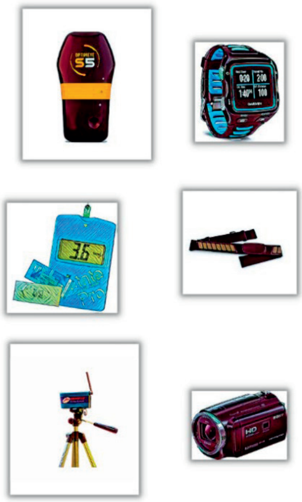

Fig 2. Illustration of the equipment used outdoors in *studies I-II*.

The simulated STTs in *study I* was performed on a 1385 m racecourse consisting of 1 lap with varied topography [uphill (38%), flat (19%), and downhill (43%)], which was divided into 6 different segments (S1-S6), according to terrain topography (see Fig 3). The maximal difference in elevation was 24 m with a total climb of 38 m. The classical sprint XC competition in *study II* was performed on a 1720 m racecourse consisting of 1 lap with varied topography [uphill (31%), flat (17%), and downhill (52%)] and the racecourse was divided into 11 different segments (S1-S11), according to terrain topography (see Fig 4). We classified sub-techniques in the classical style according to Solli et al,[54] with a per-distance classification accuracy of 96%. In the process of training and testing the algorithm, data of 9 skiers were used to train the algorithm for the racecourse, data of 7 skiers was trained for another racecourse, and the algorithm was thereafter tested on 3 skiers. Importantly, we also examined the classifications visually by comparing filtered accelerometer and gyroscope signals with representative signals of the various sub-techniques where errors were corrected based on visual inspection. In *studies II-III***,** video analysis of positioning and accidents (obstruction, fall, pole break) were performed by using publicly available television broadcast of the competitions (Norwegian Broadcasting Corporation [NRK] and TV 2 Group). Here, the racecourses were separated into segments using checkpoints according to terrain topography. For example, this method is shown in the three-dimensional illustration of the racecourse in *study II* (see Fig 4). The 16 sprint XC competitions in s*tudy III***,** were performed at four different venues (labelled competition A-D) and repeated on the same racecourse the following season. Each racecourse was separated into 5 segments (S1-S5), according to terrain topography. Competition A in the classical style was performed on a 1400 m racecourse consisting of 1 lap, maximal difference in elevation 23 m and total climb of 22 m. Competition B in the skating style was performed on a 1500 m racecourse consisting of 2 laps, maximal difference in elevation 18 m and total climb of 46 m. Competition C in the skating style was performed on a 1500 m racecourse consisting of 2 laps, maximal difference in elevation 25 m and total climb of 54 m. Competition D in the classical style was performed on a 1200 m racecourse consisting of 1 lap, maximal difference in elevation 25 m and total climb of 45 m.

Test protocols, measurements, and data analysis

In *study I***,** $\dot{V}O_2max$ was tested in an incremental uphill running test at 10.5% inclination on a treadmill with increase of 0.3 $m \cdot s^{-1}$ every min until exhaustion. The test was considered maximal effort if the following criteria were met: a $\dot{V}O_2$ plateau with increasing exercise intensity, respiratory exchange ratio (RER) above 1.10, and BLa exceeding 8 $mmol \cdot L^{-1}$. $\dot{V}O_2$ was measured continuously, and the average of the three highest 10-s consecutive measurements defined $\dot{V}O_2max$. HR_{max} was tested on a separate day outdoors, which included a 20-min warm-up, a 3–4-min uphill running with 90% effort, active recovery back to the start position, and finally a 3–4-min uphill running with maximal effort. The highest HR value during the test was defined as HR_{max}.

In *study I*, all skiers performed the two 80-m V_{max} tests in a rested state on flat terrain while skiing with the DP and G3 sub-techniques. The skiers started from a self-selected run-in in section 5 (S5) to simulate the last segment of the STT when racing downhill towards the finish sprint. The skiers were instructed to reach the highest possible speed when entering the V_{max} section (see Fig 3). Thereafter, each skier was instructed to perform two randomized STTs with conservative vs. positive pacing strategies using the classical DP sub-technique and freely chosen sub-techniques in the skating style (except in the finish sprint where the skiers were instructed to use G3) with 20-min rest in between. All skiers sprinted maximally in the V_{max} section. BLa was collected at rest and immediately after the STTs together with RPE for the total course, uphill, flat, and downhill section. To avoid the potential of saving time and energy by drafting, each individual STT had 1-min start intervals. CL and CR were determined in the V_{max} section during the V_{max} tests and in the end of the STTs for both DP and G3. The CR was calculated from the time between every second pole plant of the left pole for both styles. CL was calculated as the average speed multiplied by the cycle time (CT), and the CR was calculated as the reciprocal of CT.

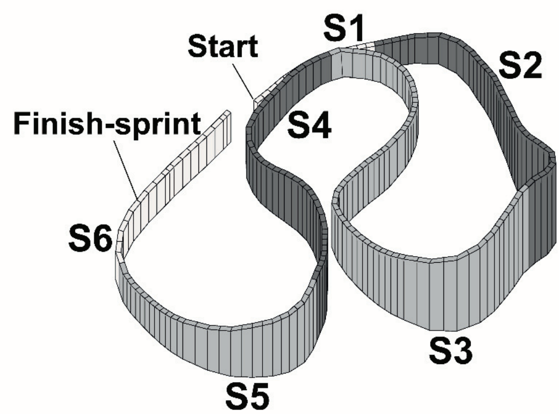

Fig 3. Three-dimensional illustration of the 6 sections (S1-S6) of the 1.4-km sprint time trial ending in an 80-m finish sprint. *Study I: Haugnes et al. 2018. The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition. International journal of Sports Physiology and Performance. Printed with permission.*

In *study II***,** all skiers performed first the individual STT followed by the knockout heats, where the skiers' position, speed and movement data were monitored by an integrated GNSS/IMU system. The sub-techniques were classified as diagonal (DIA), double poling with a kick (DK), DP and Other, the latter including tuck (TCK) and various turning techniques (TRN). The cycles were automatically segmented based on peak detection of Gaussian low pass filtered data from one axis of the gyroscope. CL was calculated as the average speed multiplied by the CT and the CR was calculated as the reciprocal of CT. In *studies II-III***,** the skiers' positioning in the heats was analysed using the television broadcast of the race. In addition, two complementary analyses were performed in *study II* (see Appendix). Here, the difference in speed and sub-technique selection between STT and heats for 7 pre-selected skiers are shown in S1 Fig. Also, the number of overtakings in the analysed competition in season 2017 in *study II* and the corresponding competition in season 2019 by skiers of a similar performance level and sex are shown in S1 Table.

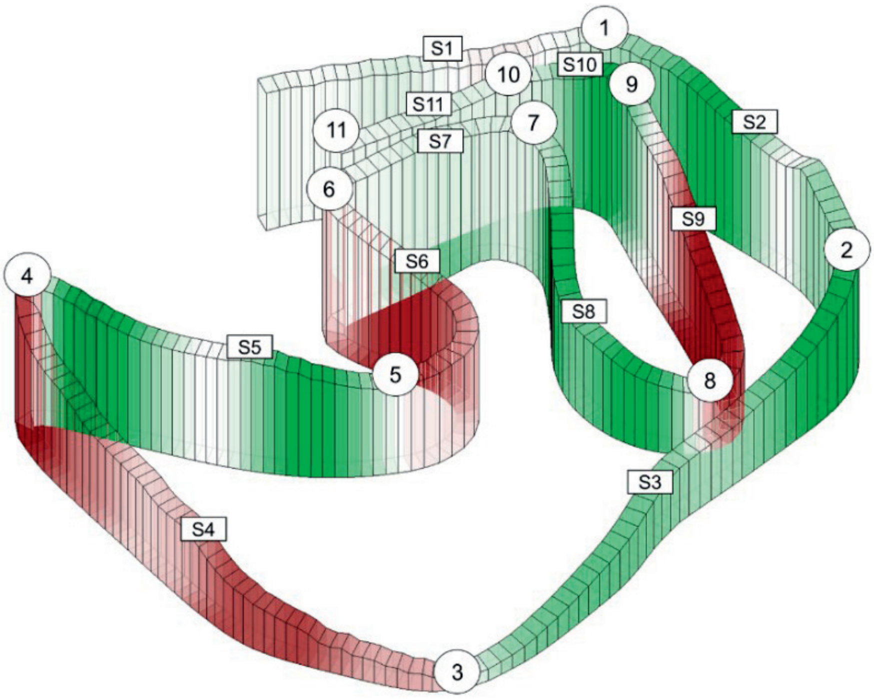

Fig 4. Three-dimensional illustration of the 1.7-km racecourse examined where the 11 segments (S1-S11) and 11 checkpoints are shown along the racecourse from start to finish. The colours represent terrain; uphill (red), flat (white), downhill (green), respectively. *Study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

Statistics

Data were checked for normality and presented as mean and standard deviation, unless otherwise stated. Shapiro-Wilk test, visual inspection of Q-Q plots, and comparison of histograms were used to assess normality. Levene's test was used to assess the homogeneity of variances. In cases where they were not normally distributed, a nonparametric alternative was used. In *studies I-III* the presented correlations between variables were analysed using Pearson's product-moment correlation coefficient test (r) or its nonparametric counterpart, Spearman rank-order correlation coefficient. A simple linear regression was used to draw trend lines in *study I*. A paired-samples t test or its nonparametric counterpart, Wilcoxon matched pairs signed-ranks tests were used to test for statistically significant differences between pacing strategy in both skiing styles in *study I*. A paired-samples t test was also used in *study III* to determine whether there was a statistically significant difference between race time in STT and the heats for the top-two in each heat, and race time in STT compared to the heats in different segments for 7 pre-selected skiers analysed in detail (see Appendix). Positioning was explored in *studies II-III*, where positioning (i.e., rank 1-6) was determined for both the heat winners and top-two in *study II* and the heat winners in *study III*. Positioning for all skiers in *studies II-III* was examined by assessing the relationship between intermediate rankings and final rankings by using Kendall tau-b correlations. The coefficient of variation ($100 \cdot SD \cdot mean^{-1}$) for V_{max} in both styles was calculated in *study I*. The intraclass correlation coefficient (ICC) was used in *study I* to assess the repeatability for V_{max} in the classical and skating style, and the repeatability for overtakings between years in *study II*. The percentage difference in *studies II-III* equals the absolute value of the change in value, divided by the average of the 2 number, all multiplied by 100. A one-way ANOVA was conducted to determine if kinematic variables were different for groups with different final rankings in *study II*, followed up by Tukey's HSD post hoc test. A two-way mixed ANOVA was conducted to determine whether there was a statistically significant mean difference in overtakings between sex on the same racecourse over time in *study III*. The magnitude of the correlation coefficients and effect sizes were interpreted as following: 0.0-0.1, trivial; 0.1-0.3, small; 0.3-0.5 moderate; 0.5-07, large; 0.7-0.9, very large; 0.9-1.0, nearly perfect.[61] Statistical significance was set at $\alpha < .05$ in all studies. Statistical tests in *studies I-III* were performed using IBM SPPS statistics version 24 software for Windows (SPSS Inc, Chicago, IL) in *study I,* STATA 16.0 software (Stata Corporation, College Station, TX, USA) in *studies II-III*, and Excel 2016 (Microsoft Corporation, Redmond, WA, USA) in *studies I-III*.

RESULTS

Study I: The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition.

This study investigated the contribution from V_{max} and $\%V_{max}$ to the finish sprint speed obtained in a simulated STT in the classical and skating style, as well as the coinciding changes in kinematic patterns and the effect of pacing strategy on the $\%V_{max}$.

The skiers achieved 9.3±0.6 and 10.3±0.6 $m \cdot s^{-1}$ for classical and skating styles on the V_{max} test, respectively, with a ~10 % speed difference between styles ($P < .001$). This speed difference was reflected in a significantly longer CL for skating compared to classical: 7.0±0.6 vs. 6.1±0.6 m ($P < .05$), whereas no significant difference in CR was seen between styles: 1.48±0.09 vs. 1.54 ±0.12 Hz, respectively. Skiing speed in the finish sprint was 3.6% faster with the conservative pacing vs. positive pacing strategy in the classic style ($P < .001$; Table 1). Although the percentage difference between pacing strategies were the same for skating (Table 1), this difference did not reach statistical significance.

The average speed in the STT was 5.9±0.3 vs. 6.1±0.4 $m \cdot s^{-1}$ for classical and 6.8±0.3 vs. 7.0±0.5 $m \cdot s^{-1}$ for skating, using the conservative and positive pacing strategy, respectively. The skiers average speed in the classical style over the total racecourse was significantly faster with positive pacing strategy compared with the conservative pacing strategy ($P < .05$; Fig 5 and Table 1), whereas no difference was seen between the pacing strategies in skating (Fig 6 and Table 1). A comparison between styles, indicates a 14% speed difference, for both pacing strategies, respectively ($P < .001$). Furthermore, positive pacing resulted in a significantly faster speed in the first sections of the racecourse (S1-S2) in both styles ($P < .05$; Fig 5 and 6). However, this speed difference levelled out in the rest of the racecourse (S3-S6), and no significant difference was seen between the strategies in the rest of the racecourse.

Table 1. Performance and physiological characteristics of 12 elite male cross-country skiers during 1.4-km sprint time-trials (STTs) ending in an 80-m finish sprint using the classic (double poling) and skating styles with conservative and positive pacing strategies, respectively (mean [SD]). *Study I: Haugnes et al. 2018. The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition. International journal of Sports Physiology and Performance. Printed with permission.*

	Conservative pacing	**Positive pacing**
CLASSIC		
BLa_{pre}, mmol·L^{-1}	10.1 (4.7)	9.0 (2.0)
BLa_{peak}, mmol·L^{-1}	13.1 (4.1)	14.5 (2.8)
Heart rate mean, %HR_{max}	82.0 (3.7)	84.3 (2.5)*
Heart rate peak, %HR_{max}	87.4 (3.7)	89.0 (2.6)*
Total (Borg 6-20)	17 (1)	19 (1)**
Uphill (Borg 6-20)	17 (1)	19 (1)**
Flat (Borg 6-20)	16 (2)	17 (2)*
Downhill (Borg 6-20)	14 (3)	15 (2)*
Race time, s	234 (11)	226 (15)*
Finish-sprint, m·s^{-1}	8.0 (0.9)$^{\#\#}$	7.8 (0.9)$^{*,\#\#}$
Finish-sprint cycle length, m	6.0 (0.4)	6.1 (0.7)
Finish-sprint cycle rate, Hz	1.35 (0.14)$^{\#\#}$	1.28 (0.15)$^{*,\#\#}$
SKATING		
BLa_{pre}, mmol·L^{-1}	9.8 (2.7)	8.8 (4.5)
BLa_{peak}, mmol·L^{-1}	13.0 (2.3)	14.3 (3.4)
Heart rate mean, %HR_{max}	84.4 (2.9)	84.2 (5.5)
Heart rate peak, %HR_{max}	89.1 (3.1)	89.2 (5.2)
Total (Borg 6-20)	17 (1)	19 (1)**
Uphill (Borg 6-20)	18 (2)	19 (2)*
Flat (Borg 6-20)	16 (2)	18 (1)**
Downhill (Borg 6-20)	14 (3)	16 (2)*
Race time, s	203 (8)	200 (15)
Finish-sprint, m·s^{-1}	8.9 (0.7)$^{\#\#}$	8.7 (0.8)$^{\#\#}$
Finish-sprint cycle length, m	6.6 (0.7)	6.8 (0.7)
Finish-sprint cycle rate, Hz	1.35 (0.10)$^{\#\#}$	1.29 (0.11)$^{*,\#\#}$

Significant difference between conservative and positive pacing, * $P < .05$; ** $P < .01$.
Significant different from the maximal speed (V_{max}) test, $^{\#}$ $P < .05$; $^{\#\#}$ $P < .01$.
BLa_{pre} Rest blood lactate, BLa_{peak} Peak blood lactate.

A significantly difference in HR response was found between the two pacing strategies in the classical style, where the average and peak values (%HR_{max}) was higher for the positive pacing compared with the conservative pacing strategy ($P < .05$; Fig 5 and Table 1). No significant difference between the skiers' peak BLa level after the STT was seen in either style. However, the skier's own perception of exertion was rated significantly higher in both styles for the total racecourse and in terrains with positive pacing compared with the conservative pacing strategy ($P < .05$; Table 1).

A positive pacing strategy resulted in significantly lower CR compared with the conservative strategy in both styles ($P < .05$; Table 1), whereas no significant difference in the skier's CL was seen. The changes in kinematic pattern from V_{max} to the last 80-m in the finish sprint in the STT were reflected with significant reduced CR: 15% vs. 11% with conservative pacing and 22% vs. 15% with positive pacing, for classical and skating styles, respectively ($P < .01$; Table 1), whereas there was no significant difference in CL.

Fig 7 shows that the skiers achieved 86±6% and 87±5% of V_{max} in the finish sprint with conservative pacing, whereas 83±6% and 84±5% was achieved using the positive pacing for classical and skating XC skiing, respectively. Fig 8 and 9 shows the correlations between the finish sprint speed vs. V_{max} and %V_{max}, respectively. Both the skiers' V_{max} and the %V_{max} were positively correlated with the finish sprint speed (all $P < .05$; Fig 8 and 9).

The skiers' CR correlated positively with the finish sprint speed in the classical style using conservative ($r = .82$, $P = .01$) and positive pacing strategy ($r = .60$, $P = .05$), respectively. In contrast, the skiers' CL in the skating style correlated positively with the finish sprint speed using conservative pacing ($r = .76$, $P = .05$), and a trend was found for positive pacing ($r = .65$, $P = .056$), respectively. Regarding the reduction in finish sprint speed in the end of the simulated STT compared with V_{max}, a trend was found between the reduction in CR and reduction in speed in the classical style using conservative and positive pacing strategy ($r = .55$ and .52, respectively, both $P = .08$), whereas a trend was found for reduction in CL and speed in the skating style using conservative ($r = .63$, $P = .052$) and positive pacing strategy ($r = .61$, $P = .08$).

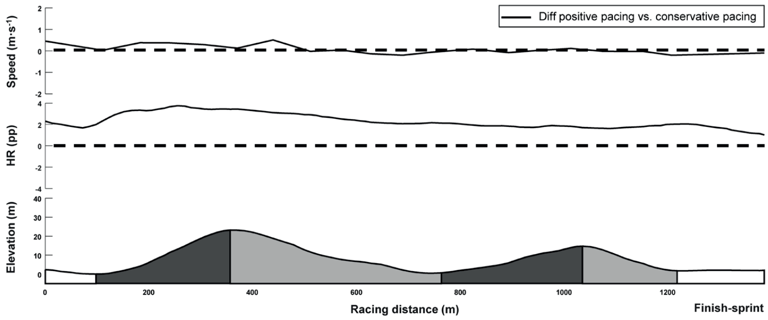

Fig 5. Mean speed difference and mean pp difference (solid lines) for 12 elite male cross-country skiers using the classic (double poling) style with conservative versus positive pacing strategy in 1.4-km STTs, respectively. HR indicates heart rate; pp, percentage point; STT, sprint time trial. *Study I: Haugnes et al. 2018. The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition. International journal of Sports Physiology and Performance. Printed with permission.*

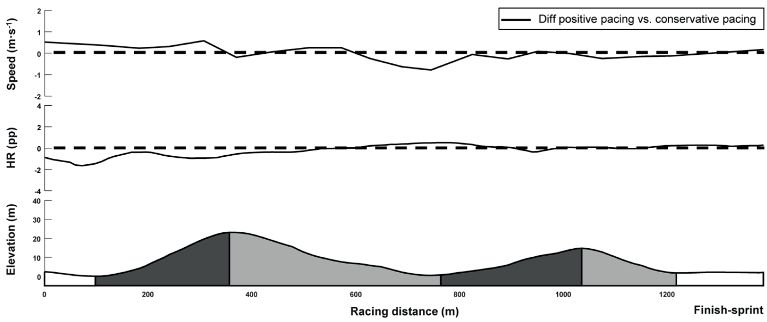

Fig 6. Mean speed difference and mean pp difference (solid lines) for 12 elite male cross-country skiers using the skating style with conservative versus positive pacing strategy in 1.4-km STTs, respectively. HR indicates heart rate; pp, percentage point; STT, sprint time trial. *Study I: Haugnes et al. 2018. The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition. International journal of Sports Physiology and Performance. Printed with permission.*

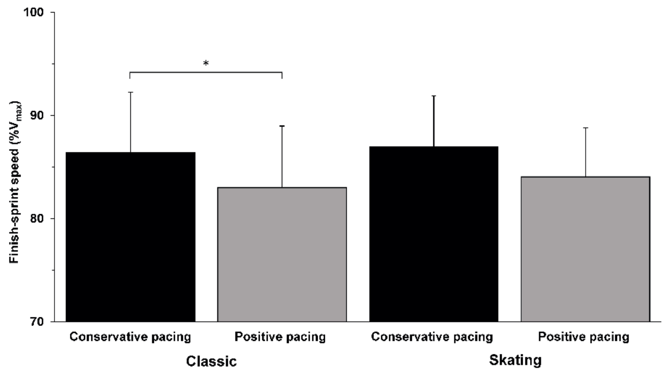

Fig 7. Finish sprint speed compared to percentage of maximal speed (%V_{max}) in an 80-m finish sprint in the end of 1.4-km STTs for elite male cross-country skiers using the classic (double poling) and skating (G3) techniques with conservative versus positive pacing strategy, respectively (mean [SD]). Significant differences between pacing strategies are indicated by * $P < .05$. STT indicates sprint time trial. *Study I: Haugnes et al. 2018. The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition. International journal of Sports Physiology and Performance. Printed with permission.*

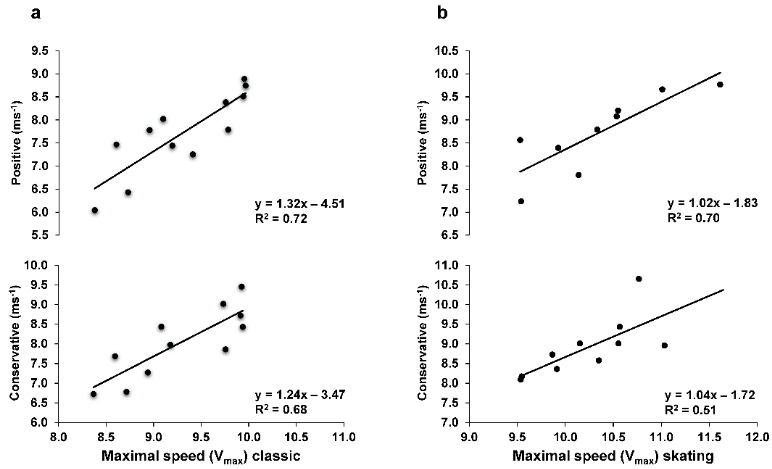

Fig 8. Finish sprint speed in relationship to maximal speed (V_{max}) in an 80-m finish sprint in the end of 1.4-km STTs for elite male cross-country skiers using the A) classic (double poling) and B) skating (G3) techniques with conservative versus positive pacing strategy, respectively. The data points represent the individual skiers and the lines were obtained by linear regression. STT indicates sprint time trial. *Study I: Haugnes et al. 2018. The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition. International journal of Sports Physiology and Performance. Printed with permission.*

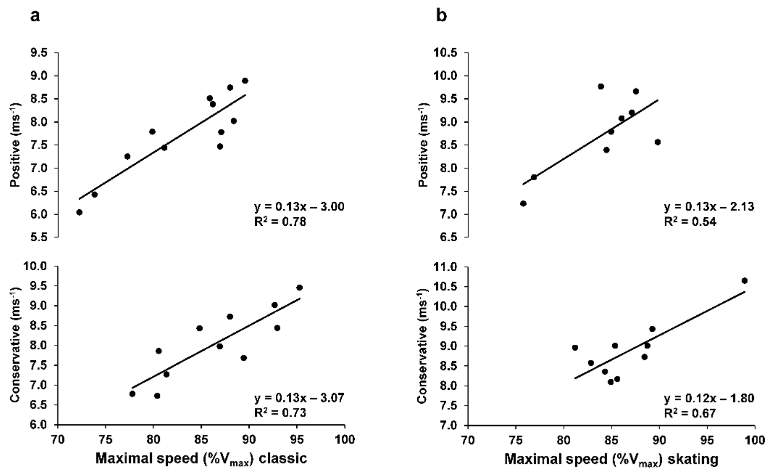

Fig 9. Finish sprint speed in relationship to percentage of maximal speed ($\%V_{max}$) in an 80-m finish sprint in the end of 1.4-km STTs for elite male cross-country skiers using the A) classic (double poling) and B) skating (G3) techniques with conservative versus positive pacing strategy, respectively. The data points represent the individual skiers and the lines were obtained by linear regression. STT indicates sprint time trial. *Study I: Haugnes et al. 2018. The effect of maximal speed ability, pacing strategy, and technique on the finish sprint of a sprint cross-country skiing competition. International journal of Sports Physiology and Performance. Printed with permission.*

Study II: The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition

This study examined the association of race tactics for performance in the heats of an international sprint XC skiing competition in the classical style.

STT rank and the final rank for the skiers in this competition correlated positively [$r_s(28) = .72$, $P = .001$)]. Skiing times for top-two and number of incidents are shown in Table 2. We found that the top-two skiers were on average 4% slower in the heats than in the STT [average heat time: 237±4 vs. STT: 228±4 (s)], with the difference being significant [$t(9) = -6.6$, $P = .001$, $d = 2.2$)].

In total of 124 overtakings were observed during the heats, that is ~16 overtakings in each heat. To understand how the skiers performed the overtakings on the different parts of the racecourse better, we adjusted the overtakings for segment length, and this resulted in ~10 overtakings per 100 m from the start to the final uphill segment (S2 to S9), and only ~3 per 100 m on the two last segments (S10 to S11). Most overtakings were observed in the longest uphills (S4 and S9), although many overtakings were also performed in all types of terrain.

Table 2. Skiing time for the top-two finishers and number of incidents during a 1.7-km classical sprint cross-country skiing race for elite male skiers. Presented as absolute values [N=16]. *Study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

Variable	QF 1	QF 2	QF 3	QF 4	QF 5	SF 1	SF 2	F
Heat rank 1 (s)	236.00	235.00	238.10	237.90	243.90	233.20	232.40	230.40
Heat rank 2 (s)	236.50	235.40	238.70	238.20	244.10	233.40	232.40	231.50
Heat rank 1 (%STT_{top1})	6.9	6.5	7.7	7.6	9.9	5.8	5.4	4.6
Heat rank 2 (%STT_{top1})	7.1	6.6	7.9	7.7	10.0	5.8	5.4	5.1
Obstruction (n)	3	2	1	3	0	3	1	1
Fall (n)	0	0	0	1	0	0	0	0
Pole break (n)	0	0	0	0	2	0	0	0
Yellow card (n)	0	0	0	0	0	0	0	0

Abbreviations: STT, time-trial; QF, quarterfinal; SF, semi-final; F, Final; %STT_{top1}, percentage of the sprint time-trial winner time.

The relationship between intermediate ranks and final ranks during the heats is shown in Fig 10. The strength of the correlation increased segment-by-segment throughout the racecourse and was clearly strongest in the last segments before the finish sprint.

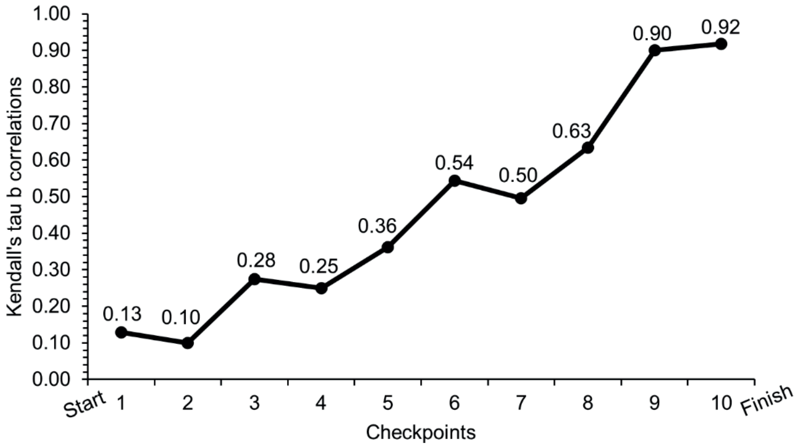

Fig 10. Kendall's tau-b correlations. The relationship between intermediate ranks and final rank during the heats of a classical sprint cross-country skiing race for elite male skiers [N=30]. *Study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

The positioning of heat winners and top-two at different checkpoints during the racecourse is shown in Table 3. As presented here, one can see that 75% of those who won the heats were positioned first in the final uphill segment, whereas 94% of the top-two were being positioned first or second. Fig 11 shows the average time behind the leader in each segment, speed profiles, and positioning for all heats. From the start until the final uphill (S9) all skiers were within 4 seconds behind of the skier in the front of the heat, whereas in the final part of the race top-four were generally faster than the skiers ranked 5-6 who either could not keep up with the rest of the heat or decided to give up.

Table 3. Percentage of heat winners (left part) and top-two finishers (right part) positioned at rank 1-6 at the 11 checkpoints during the heats of a 1.7-km classical sprint cross-country skiing race for elite male skiers. Presented as percentages [N=16]. *Study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

Variable	**Heat winner**						**Top 2-finishers**					
Checkpoints 1-11	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**
1. Out of stadium	25.0%	12.5%	25.0%	12.5%	12.5%	12.5%	12.5%	31.3%	18.8%	18.8%	6.3%	12.5%
2. First downhill	25.0%	12.5%	25.0%	12.5%	12.5%	12.5%	12.5%	31.3%	12.5%	18.8%	6.3%	18.8%
3. End of first downhill	50.0%	0.0%	12.5%	25.0%	12.5%	0.0%	31.3%	18.8%	12.5%	18.8%	12.5%	6.3%
4. End of first uphill	37.5%	12.5%	0.0%	25.0%	25.0%	0.0%	31.3%	25.0%	6.3%	12.5%	18.8%	6.3%
5. End of second downhill	37.5%	12.5%	37.5%	0.0%	12.5%	0.0%	31.3%	25.0%	25.0%	6.3%	6.3%	0.0%
6. End of second uphill	50.0%	12.5%	25.0%	0.0%	12.5%	0.0%	43.7%	25.0%	18.8%	6.3%	6.3%	0.0%
7. Before third downhill	75.0%	0.0%	12.5%	0.0%	0.0%	12.5%	50.0%	12.5%	31.3%	0.0%	0.0%	6.3%
8. End of third downhill	75.0%	0.0%	12.5%	0.0%	0.0%	12.5%	50.0%	25.0%	18.8%	0.0%	0.0%	6.3%
9. End of third uphill	75.0%	12.5%	12.5%	0.0%	0.0%	0.0%	43.8%	50.0%	6.3%	0.0%	0.0%	0.0%
10. Before the finish-sprint	75.0%	12.5%	12.5%	0.0%	0.0%	0.0%	43.8%	50.0%	6.3%	0.0%	0.0%	0.0%
11. Finish	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%	50.0%	0.0%	0.0%	0.0%	0.0%

Checkpoint 11 Finish: All heat winners were ranked 1, whereas top 2-finishers were either ranked 1 or 2.

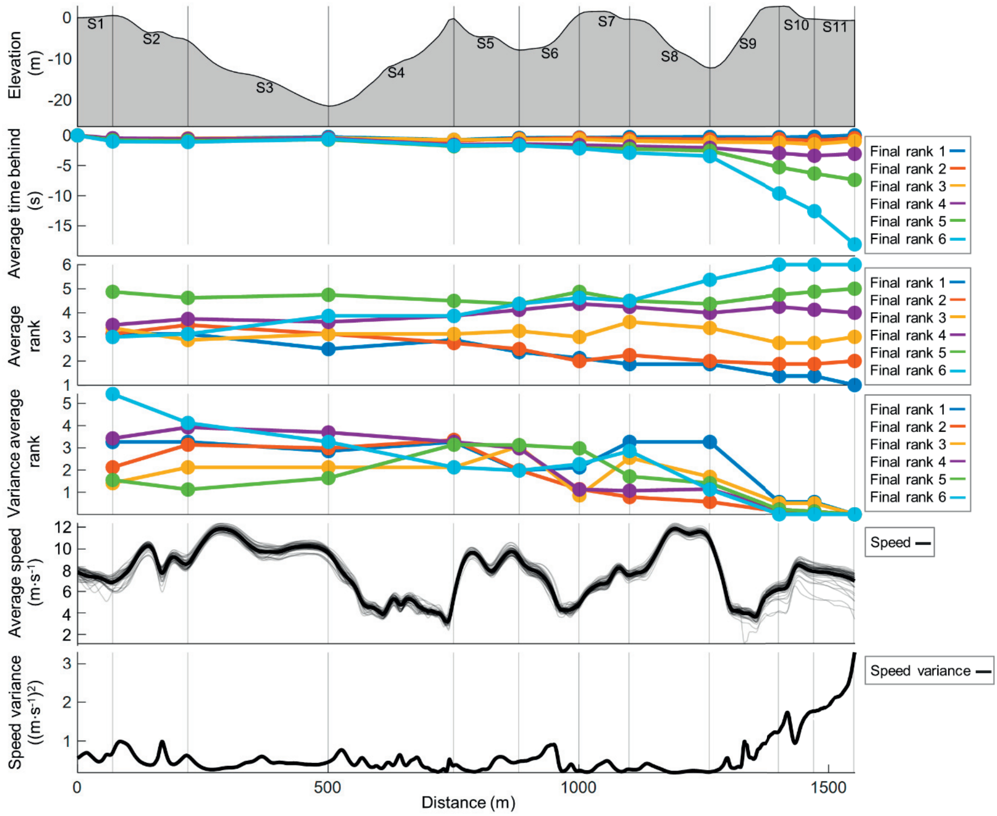

Fig 11. Time behind, speed, and positioning. The average time behind the winner, intermediate rankings, and skiing speed across the racecourse in 11 segments (S1-S11) during the heats of a classical sprint cross-country skiing race for elite male skiers [N=29 time and speed, N=30 positioning]. *Study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

The distribution of sub-techniques in relation to the racecourse for all skiers during the finals is shown in Fig 12. Every individual skier is presented in each heat according to the order of final rank. As demonstrated here, all skiers used a similar sub-technique selection along the racecourse.

The percentage use of different sub-techniques (DIA, DK, DP, OTHER) in relation to the distance for the STT (N=7) and heats (N=28) is shown in Fig 13. As presented, there is no statistical difference in the use of sub-technique selection in this competition.

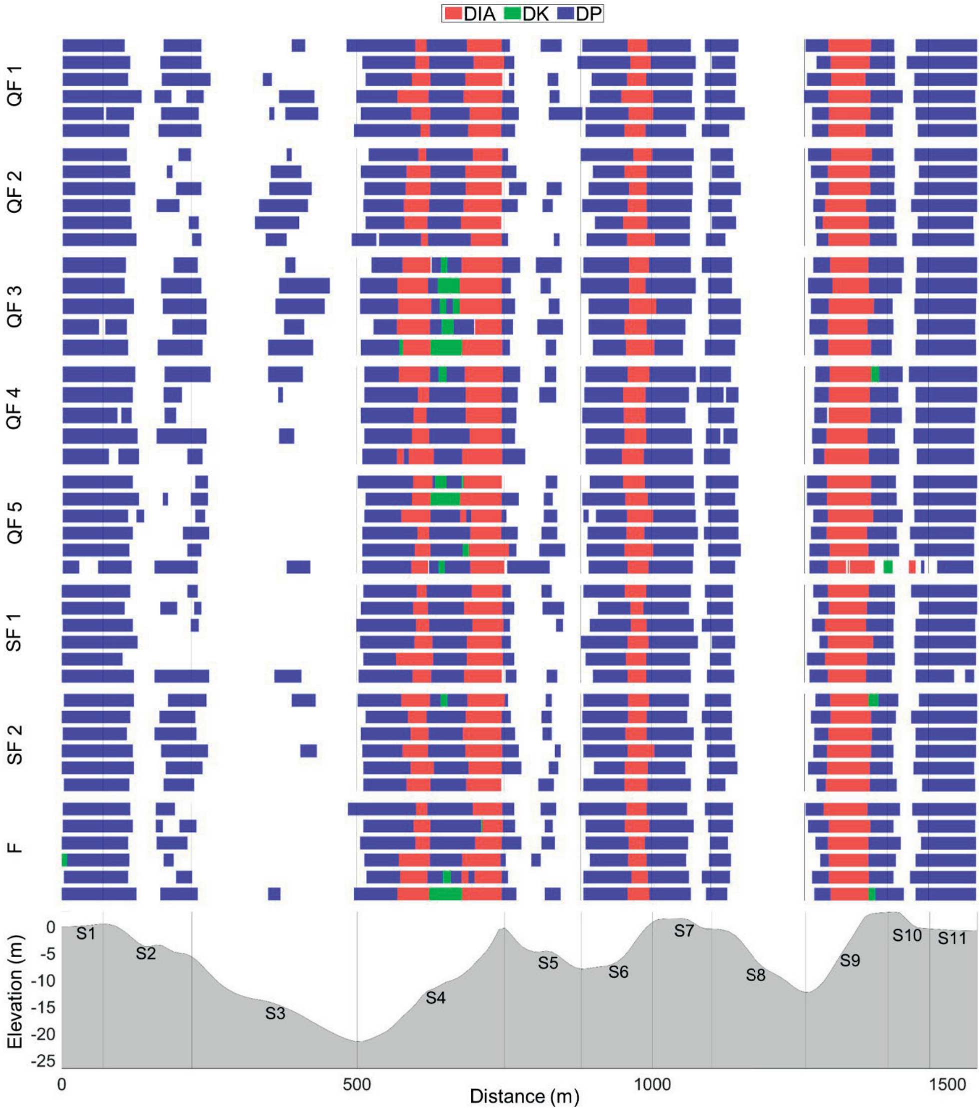

Fig 12. Individual sub-technique selection. The individual use of sub-techniques (diagonal stride [DIA], double poling with a kick [DK], double poling [DP]) and [Other] including tuck and turning techniques) across the racecourse in 11 segments (S1-S11) during the heats of a classical sprint cross-country skiing race for elite male skiers. The skiers are presented according to the order of ranking from top 1st to bottom 6th [N=28]. *Study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

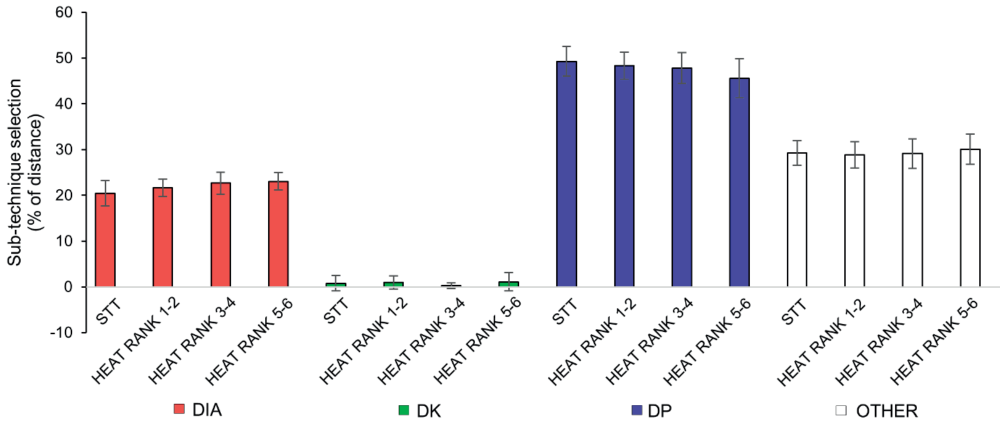

Fig 13. Sub-technique selection in relation to distance. The percentage use of sub-techniques (diagonal stride [DIA], double poling with a kick [DK], double poling [DP]) and [Other] including tuck and turning techniques) in relation to distance across the racecourse during the sprint time-trial and heats of a classical sprint cross-country skiing race for elite male skiers. Error bars indicate SD [N=28]. *Study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

Table 4 shows speed, CL, and CR in the last uphill segment (S9) for the skiers ranked 1-2 (N=16), 3-4 (N=16) and 5-6 (N=13). Here in this segment, the speed differed significantly between groups [$F(2,42) = 32.32$, $P = .001$, ω2 = 0.58)], with the skiers ranked 1-2 and 3-4 showing significantly higher speed than those ranked 5-6 (both, $P = .001$), while the corresponding difference between heat rank 1-2 and 3-4 was not differently ($P = .600$). The CL differed significantly between groups [$F(2,42) = 7.35$, $P = .002$, ω2 = 0.22)], with the skiers ranked 1-2 and 3-4 showing a significantly longer CL than those ranked 5-6 ($P = .003$ and .007). In contrast, the difference in CL between heat rank 1-2 and 3-4 was not differently ($P = .936$). However, CR differed significantly between groups [$F(2,42) = 7.02$, $P = .002$, ω2 = 0.21)], where the skiers ranked 1-2 and 3-4 showing a significantly higher CR than those ranked 5-6 ($P = .003$ and .012), while the difference between heat rank 1-2 and 3-4 was non-significant ($P = .838$).

Table 4. Cycle characteristics in the diagonal sub-technique during the final uphill segment in a 1.7-km classical sprint cross-country skiing race for elite male skiers. Values are mean ± SD [N=27]. *Study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

Variable	Heat rank 1-2	Heat rank 3-4	Heat rank 5-6
Speed ($m \cdot s^{-1}$)	4.15 ± 0.12^{c}	4.08 ± 0.18^{c}	$3.62 \pm 0.25^{a,b}$
CL (m)	1.45 ± 0.08^{c}	1.44 ± 0.08^{c}	$1.35 \pm 0.07^{a,b}$
CR (Hz)	1.43 ± 0.05^{c}	1.42 ± 0.06^{c}	$1.34 \pm 0.10^{a,b}$

Abbreviations: CL, cycle length; CR, cycle rate. The letters indicate statistically differences from heat rank 1-2 (a), heat rank 3-4 (b), or heat rank 5-6 (c) ($P < 0.05$).

Study III: The influence tactical of positioning on performance in sprint cross-country skiing

This study examined the association of positioning on performance in the heats of sprint XC skiing competitions among men and women and its consistency over repeated competitions held on the same racecourse.

STT rank and the final rank correlated strongly for the men in the competitions using both the classical (ρ = .65-.82, all $P < .01$) and skating styles (ρ = .54-.82, all $P < .01$), except for the 2019-2020 season in the classical competition A ($P = .23$). In comparison, moderate to large positive correlations were found between STT rank and the final rank for women in the classical style (ρ = .40-.78, $P < .05$) and large positive correlations in the skating style (ρ = .57-.80, all $P < .01$).

Table 5 shows overview of topography, weather, snow temperature, performance level, and number of incidents for all competitions. Table 6 shows the heat winner's positions in the heats where ~53% of men and ~69% of women in the classical style, and ~63% of men and ~75% of women in the skating style, were positioned first in the heat at the last checkpoint before the start of the finish sprint.

Table 5. Overview of two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style). Presented as absolute values [N=30 male and N=30 female skiers within each of the eight competitions in this study]. *Study III: Haugnes et al. 2023. The influence of tactical positioning on performance in sprint cross-country skiing. PLoS One.*

Variable	Competition A classical				Competition B skating				Competition C skating				Competition D classical			
	Women 1st yr	Men 1st yr	Women 2nd yr	Men 2nd yr	Women 1st yr	Men 1st yr	Women 2nd yr	Men 2nd yr	Women 1st yr	Men 1st yr	Women 2nd yr	Men 2nd yr	Women 1st yr	Men 1st yr	Women 2nd yr	Men 2nd yr
FIS (sprint points)	34 ± 24	42 ± 24	39 ± 26	40 ± 23	31 ± 25	43 ± 21	41 ± 26	37 ± 19	40 ± 25	46 ± 23	43 ± 27	40 ± 19	27 ± 14	38 ± 21	30 ± 18	35 ± 18
Air temp (°C)	-0.5	-0.6	-4.0	-4.0	-1.9	-1.9	-2.0	-2.0	0.8	0.8	2.7	2.7	0.7	0.8	0.5	0.0
Snow temp (°C)	-2.6	-2.5	-2.6	-2.6	-2.8	-2.8	-1.8	-1.8	0.2	0.3	-2.6	-2.6	-1.4	-1.2	-1.3	-1.3
Distance (m)	1400	1400	1400	1400	1500	1500	1500	1500	1500	1500	1500	1500	1214	1214	1200	1200
HD (m)	23	23	23	23	18	18	18	18	20	20	25	25	25	25	24	24
MC (m)	22	22	22	22	12	12	12	12	16	16	22	22	23	23	21	21
TC (m)	43	43	43	43	46	46	46	46	40	40	54	54	36	36	45	45
Laps (n)	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
Pole breaks (n)	0	1	0	1	1	2	0	1	2	0	1	1	0	0	0	0
Falls (n)	1	0	0	0	1	2	2	0	2	0	3	3	1	1	0	2
Obstructions (n)	3	3	4	0	1	2	6	4	1	1	1	6	9	4	4	3
Yellow cards (n)	4	2	0	2	0	0	1	1	0	0	0	0	0	3	3	0

Abbreviations: HD, height difference; MC, max climb; TC, total climb.

Table 6. The average percentage of heat winner classical (left part) and heat winner skating (right part) positioned at rank 1-6 at the 5 checkpoints during two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style). Presented as percentages [N=8 male and N=8 female skiers within each of the eight competitions in this study]. *Study III: Haugnes et al. 2023. The influence of tactical positioning on performance in sprint cross-country skiing. PLoS One.*

Variable	Heat winner classical						Heat winner skating					
Checkpoints 1-5 Women	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**
1. Out of stadium	44%	19%	12%	0%	12%	13%	38%	31%	6%	19%	6%	0%
2. End of first part	44%	29%	16%	0%	4%	7%	31%	44%	25%	0%	0%	0%
3. End of middle part	50%	28%	16%	0%	6%	0%	50%	31%	13%	6%	0%	0%
4. Before the finish sprint	69%	25%	6%	0%	0%	0%	75%	25%	0%	0%	0%	0%
5. Finish	100%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
Checkpoints 1-5 Men	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**
1. Out of stadium	34%	25%	16%	6%	19%	0%	39%	20%	20%	7%	7%	7%
2. End of first part	29%	39%	14%	11%	7%	0%	44%	31%	0%	6%	19%	0%
3. End of middle part	44%	34%	6%	9%	7%	0%	50%	44%	6%	0%	0%	0%
4. Before the finish sprint	53%	41%	3%	0%	3%	0%	63%	37%	0%	0%	0%	0%
5. Finish	100%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%

Checkpoint 5 Finish: All heat winners were ranked 1.

Fig 14 shows the total number of overtakings for the competitions, and Fig 15 shows the number of overtakings on the different segments. For both sexes, an average of ~20 and ~16 overtakings were observed in each heat for the classical and skating style, respectively.

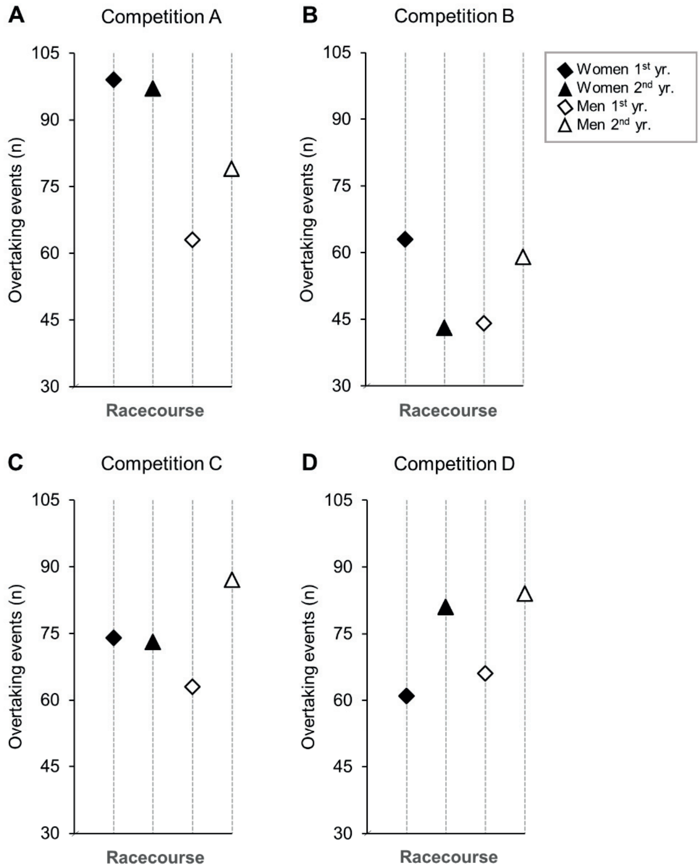

Fig 14. The number of overtakings. Overtakings in two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style) [(N=30 male and N=30 female skiers within each of the eight competitions in this study)]. *Study III: Haugnes et al. 2023. The influence of tactical positioning on performance in sprint cross-country skiing. PLoS One.*

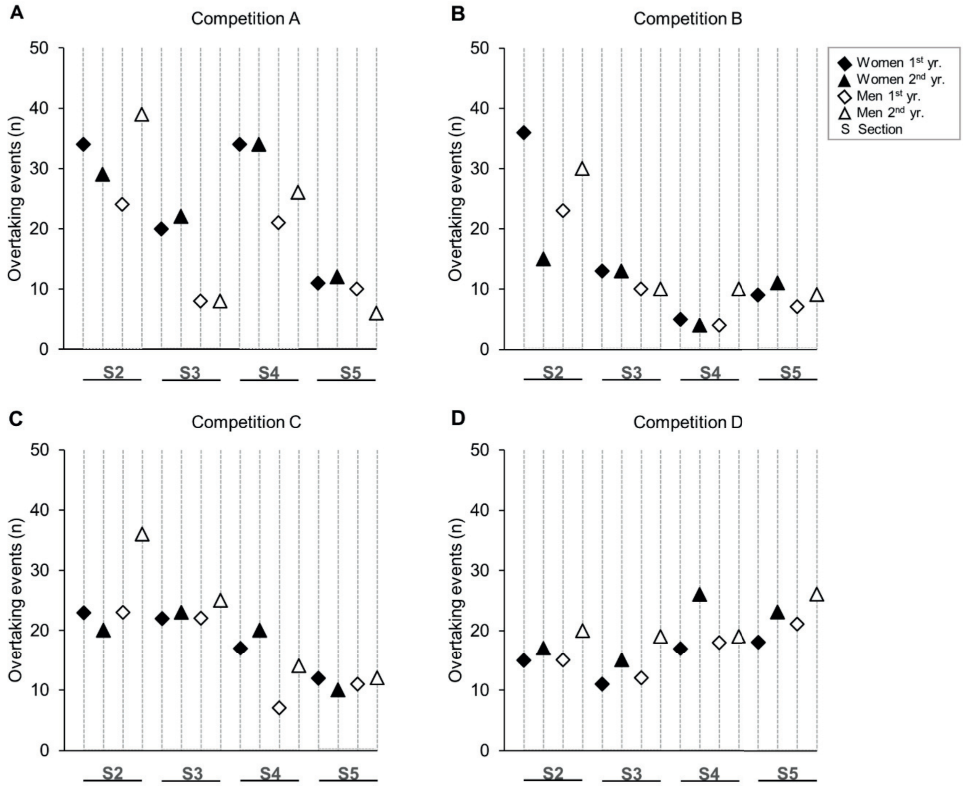

Fig 15. The number of overtakings in segments. Overtakings in two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style) [(N=30 male and N=30 female skiers within each of the eight competitions in this study)]. *Study III: Haugnes et al. 2023. The influence of tactical positioning on performance in sprint cross-country skiing. PLoS One.*

We did not find any significant interactions between sex and seasons on overtakings in any of the competitions (*P* = .086-0.91), nor was it found significant differences in the number of overtakings across seasons for any of the competitions (*P* = .051-.796). In contrast, it was found a significant difference in the number of overtakings between sexes for competition A (*P* = .004), but not for the competitions B-D (*P* = .692-.849).

Fig 16 shows the relationship between intermediate ranks and final ranks at the various checkpoints for all skiers during the heats. For men, the average correlation (τ) ranged from 0.24 to 0.70 in the classical style and 0.20 to 0.84 in the skating style. For women, the average correlation ranged from 0.28 to 0.70 in the classical style and 0.23 to 0.81 in the skating style.

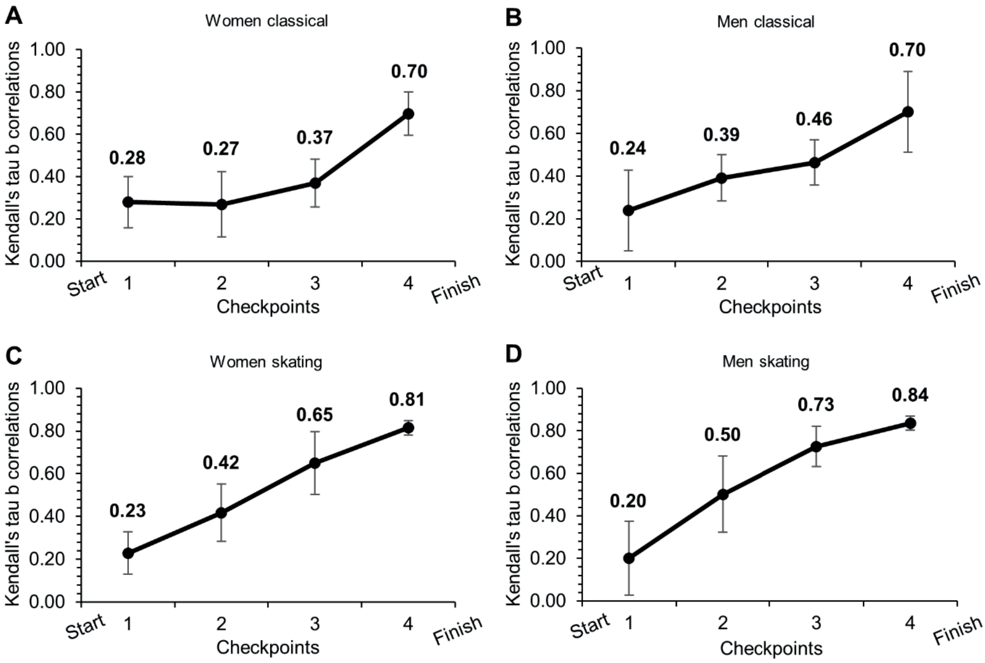

Fig 16. Kendall's tau-b correlations. The relationship between intermediate ranks at given checkpoints and final rank in two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style) [N=30 male and N=30 female skiers within each of the eight competitions in this study]. *Study III: Haugnes et al. 2023. The influence of tactical positioning on performance in sprint cross-country skiing. PLoS One.*

DISCUSSION

The primary objective of this thesis was to explore race tactics in sprint XC skiing by investigating within-race determinants of heat performance and finish sprint ability in on-snow competitions. The main findings are summarised here: In *study I*, ~85% of the skiers' V_{max} were obtained in the finish sprint in both styles and pacing strategies, with V_{max} and $\%V_{max}$ contributing similarly (R^2 = 51-78%) to explain the overall variance in finish sprint speed. The main reason for reductions in skiing speed in the finish sprint were mainly explained by reduced CR in both styles, without any changes in CL. In the classical style, the use of conservative pacing resulted in a 3.6% faster finish sprint (not statistically for skating), whereas positive pacing led to a faster speed for the total racecourse compared with the conservative pacing (no difference between the strategies in skating). In *study II*, a large correlation was found between STT rank and the final rank. The skiers were ~4% slower in the heats compared to the STT, where this difference was particularly evident in the segments before the last uphill. On average, ~16 overtakings occurred in each heat, in which ~10 overtakings per 100 m were performed from the start to the final uphill segment, and only ~3 overtakings in the two last segments of the race. As much as 94% of top-two finishers were positioned at the front of the heat when approaching the final uphill, where top-four was generally faster than the skiers ranked 5-6 in the heats, by employing longer CL and higher CR in DIA. We observed a relatively similar sub-technique selection across skiers within and between heats. In *study III*, moderate to large positive correlations between STT rank and final rank were found for both male and female races in both styles. The correlation coefficients between intermediate ranks and final ranks gradually increased from the start of the finish of the heats and were strongest at the last checkpoint (~100 meters before the finish) for both styles and sexes. Here, ~94% of the heat winners were ranked top-two at the last checkpoint. For both sexes, on average ~20 overtakings in the classical and ~16 overtakings in the skating style were observed in each heat. The greater possibility for positioning in the classical style compared to skating is likely the reason for why the heats were decided at an earlier stage in the skating style compared to classical for both sexes. There were no significant differences in overtakings between seasons for competitions organized on the same type of racecourse under comparable racing conditions.

Pacing strategy and race tactics

In *study I,* the use of conservative pacing in the 1.4-km simulated STTs showed that the skiers achieved 3.6% faster finish sprint speed (not statistically for skating), whereas positive pacing led to a faster average speed for the total racecourse. In any event, only a fraction of a second can divide the top finishers (see Table 2), and using a conservative pacing strategy, when possible, would therefore be beneficial for most skiers. However, sprint XC skiing competitions nowadays includes a technique zone in the classical style,[62] often in a steep uphill as seen in *study II* (see Fig 4), where the skiers cannot use the DP sub-technique. At the time when the data collection was performed in *study I,* the skiers were allowed to perform DP throughout the entire racecourse, where many skiers were using skating skis (glide-waxed skis) instead of grip-waxed classic skis. It is unclear if the findings regarding classical style in *study I* are applicable since performing DP with skating skis result in much faster skiing speed. Therefore, future research examining sprint XC skiing outdoors in the classical style should include grip-waxed classic skis.

The race tactics in the heats explored in *studies II-III* are the first to be investigated in actual on-snow competitions. In comparison, race tactics has been shown to be an important performance determinant in other endurance sports, such as for example cycling,[63-65] middle-distance-running,[66-68] and short-track speed skating.[69-71] The large positive correlation found for men and the moderate to large positive correlations found for women, between the STT rank and the final rank in *studies II-III*, is in line with Spencer et al.,[10] who reported moderate to very large correlations for both styles and sexes. The correlations in *studies II-III* show that a relatively large portion of the variance in final rank in the heats was not explained by STT performance, and this demonstrates the importance of heat tactics and being able to perform in multiple heats throughout an entire competition day. In contrast to Spencer et al.,[10] no sex-difference in correlations between STT rank and final rank was found in *study III*. A reason may be that there was a more homogeneous group of women in *study III* compared to the study of Spencer et al.,[10] and that women nowadays compete more often in the same racecourse as men.

The skiers in *study II* chose to ski close to the leader of the group from the start of the race until the final uphill segment, where top-four decided the heats by being generally faster compared to the skiers ranked 5-6 by utilizing longer CL and higher CR in DIA. This race-strategy resulted in ~4% slower speed at the beginning of the heats compared to the STT, where 50% of the heat winners were being positioned first after one-third of the racecourse in the heats with substantial changes in positioning of the remaining part of the racecourse where the speed difference gradually levelled out. As a result, ~16 overtakings were performed in each heat, in which ~10 overtakings per 100 m were performed from the start to the final uphill segment, and only ~3 overtakings were performed in the two last segments of the race. Furthermore, ~94% of the heat winners in *studies II-III* positioned themselves gradually further towards the front of the heat and were ranked top-two at the last checkpoint before the finish sprint. In contrast, Andersson et al.[39] found that most of the heat winners (61%) of both sexes were first already after the start of the heats. A reason for this difference is that *studies II-III* included the world's best XC sprint skiers competing in homogenous heats, whereas there was a larger heterogeneity in performance level among the skiers investigated by the time of the study of Andersson et al.[39]

Furthermore, we found that the strength of the correlations between intermediate ranks at given checkpoints and final ranks in *studies II-III* increased gradually throughout the heats, with the largest correlations at the last checkpoint. Notably, we found larger correlation coefficients at the last checkpoint in the skating compared to the classical style (τ = ~0.82 vs. ~0.70) for both sexes in *study III.* This result could indicate that the competitions in the skating style were decided at an earlier stage than the classical style. Of course, one should be careful interpreting correlation coefficients, but it is more difficult to pass other skiers in the skating style compared to the classical style since each skier occupies more of the track width in the skating style due to the zig-zag movements. This finding is supported by indications of less accidents (see Table 5) and more overtakings (~20 vs. ~16) in the classical compared to the skating style. In the latter the highest-ranked skiers positioned themselves more often in the front of the heats at an earlier stage (see Fig 16 and Table 6), and thus controlled the speed and avoided accidents. Although different racecourses and external conditions would affect the skiers' race tactics and require different tactical decisions,[72,73,74] there was no significant difference in number of overtakings between the seasons investigated for both sexes and styles in *study III*, indicating that the number of overtakings on the same racecourse with skiers on the same performance level and external conditions are relatively consistent.

Finish sprint ability

Approximately ~85% of the skiers' V_{max} in *study I* was obtained in the end of the 1.4 km simulated STTs using both the conservative and positive pacing strategy, which is in line with previous research investigating the finish sprint ability on skis and roller skis.[1,27,28] A novel finding was the contribution from V_{max} and $\%V_{max}$ to the finish sprint speed in the STTs using the classical and skating styles, which explained 51-78% of the overall variance in finish sprint speed in all cases, respectively. The reduction in speed from the V_{max} to the finish sprint in the STTs was explained by 11-22% reduced CR in both styles, with any significant reduction in CL. In previous studies investigating the finish sprint speed at the end of simulated sprint XC competitions, Zory et al.[24] and Vesterinen et al.,[27] also showed a reduction in CR in DP and G3, respectively. A possible explanation for the reduction in CR seen in *study I* is that the muscles in the upper extremities was most likely affected by fatigue, as shown in a DP sprint on snow by Zory et al.[26] Moreover, the fact that an important factor in DP is the rapid repositioning of the leg muscles[32,75] should be considered when discussing the loss of speed. The difference in temporal pattern changes associated with the reduction in finish sprint speed in the STTs is shown for the first time in *study I* and is likely explained by the different constraints of the skiing styles, where propulsion time in DP is reduced by higher speed,[32] and every propulsion lasts likely as little as ~0.2 second at typical finish sprint speeds.[31] This short period of time makes production of propulsion and CL challenging when sprinting in a fatigued state, which most likely forces the skiers to reduce the speed loss by maintaining CR.[4,35] Conversely, in skating, the skiers can push off when gliding, and in contrast to DP, the skiers can maintain push off times by adapting the angling of their skis, which causes longer cycles in G3 compared to DP.[76] Practitioners should take this into consideration when training on aiming to increase V_{max} and prevent negative effects of fatigue on speed when sprinting at the end of sprint XC skiing competitions.

Methodological considerations and practical perspectives

The deeper mechanisms related to fatigue in *study I*, such as force production or muscle activity patterns were not examined during the V_{max}, nor in the STTs. Although, we controlled the skiers' intensity by using RPE, collection of BLa before and after testing, and continuously monitored HR throughout the racecourse, we did not provide an explanatory model for the reduction in CR observed in both styles. This should be further explored in future studies examining the ability to attain a high speed during the finish sprint. Fortunately, the publicly available television broadcast of the competitions in *studies II-III* was of high quality, but this analysis method is most likely not feasible during training and competitions without broadcasting. Therefore, the utilization of sensor technology, especially for classification of intermediate rankings in the heats instead of using cameras, should be further developed in follow-up studies.

By using a holistic approach, the findings of the current thesis provide a better understanding about race tactics in the heats. However, the interpretation of the most optimal race tactics identified in this thesis is based on the self-selected race strategies of the best skiers in the competitions investigated. Naturally, the external conditions together with both the individual and opponents' strengths and weaknesses will influence the skier's choice of race strategy, which remains to be investigated in future studies. Therefore, male, and female skiers' athletic behaviour should further be explored, during different competitions, where the effectiveness and metabolic cost of the skiers' technique distribution and corresponding kinematic patterns together with speed profiles and positioning should be examined. This type of information will be of high interest for media, spectators, organisers, and could potentially help practitioners optimise their race strategies and contribute to sprint for the win in XC skiing.

CONCLUSIONS

In *study I,* the skiers performed ~85% of their V_{max} in the last 80-m finish sprint during the simulated 1-4 km STTs. A combination of high V_{max} and a high utilization of V_{max} was needed to sprint fast in the finish sprint, both in DP and G3 skating, and this was independent of pacing strategy. In *study II,* a clear reduction in the number of overtakings was observed in the end of the heats where a top-ranked position before the final uphill segment in combination with higher speed by utilising longer CL and higher CR in the DIA sub-technique were the main performance determinants. As seen, a race analysis consisting of data from the use of sensor technology together with classification of intermediate rankings in combination with an understanding of each skiers' strengths and weaknesses could be crucial for success in sprint XC skiing. In *study III,* a gradually larger importance of being positioned at the front of the heats was observed, with most of the heats being decided before the start of the finish sprint both among men and women in the classical and skating styles. Notably, the heats were decided at an earlier stage in the skating style compared to the classical style for both sexes, and the greater possibilities for positioning when using the classical style is likely the reason for this difference between styles. The number of overtakings observed was relatively consistent across seasons for competitions on the same racecourse under comparable external conditions.

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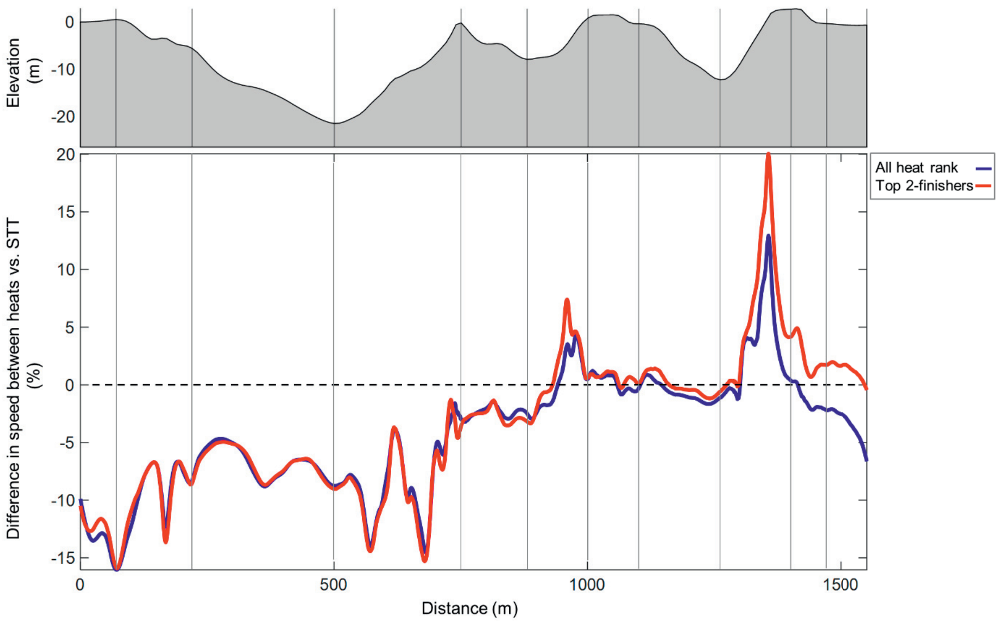
APPENDIX

The supporting information reproduced here was used in *study II*: 7 skiers examined in detail both in the STT and the heats were slower in the first parts of the heats compared to the STT (see S1 Fig); S1-3 [56±1 vs. 51±1 (s)] and S4-5 [71±1 vs. 66±2 (s)], with the difference being significant for S1-3 [t(6)= -7.7, *P* = .001, d = 4.5)] and significant for S4-5 [t(6)= -6.1, *P* = .001, d = 3.3)]. STT and segment times in the heats did not significantly differ during the middle part and the last parts of the racecourse; S6-7 [30±1 vs. 30±1 (s), t(6) = -.9, *P* = .386, d = 0.4)], S8-9 [45±5 vs. 44±2 (s), t(6)= -0.4, *P* = .704, d = 0.2)] and S10-11 [23±2 vs. 21±1 (s), t(6)= -7.8, *P* = .466, d = .4)]. However, three of the examined skiers in the heats finished as number 5-6 in the QF.



S1 Fig. Percentage difference. The difference in speed profile between the heats and the sprint time-trial in seven pre-selected skiers during a 1.7 km classical sprint cross-country skiing race for elite male skiers. [N=7 All heat rank, N=4 Top 2-finishers]. *S1 Figure used in study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

S1 Table. The number of overtakings during a repeated classical sprint cross-country skiing race for elite male skiers performed in the same racecourse in 2017 and 2019. Presented as absolute values [N=60]. *S1 Table used in study II: Haugnes et al. 2022. The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS One.*

Variable	QF 1		QF 2		QF 3		QF 4		QF 5		SF 1		SF 2		F		Total	
	2017	2019	2017	2019	2017	2019	2017	2019	2017	2019	2017	2019	2017	2019	2017	2019	2017	2019
Checkpoint 1-2	0	3	1	2	2	2	1	0	0	3	0	0	2	3	4	1	10	14
Checkpoint 2-3	5	4	2	1	3	5	1	4	1	5	2	0	4	1	1	0	19	20
Checkpoint 3-4	6	2	2	2	4	3	3	5	4	6	0	0	2	5	4	5	25	28
Checkpoint 4-5	1	1	2	0	3	0	1	0	2	0	3	0	1	0	0	0	13	1
Checkpoint 5-6	3	0	3	2	0	1	1	3	3	0	0	1	2	1	1	1	13	9
Checkpoint 6-7	0	1	0	1	3	0	5	1	2	1	1	0	0	3	0	2	11	9
Checkpoint 7-8	0	1	0	3	2	0	4	0	3	0	1	0	1	0	0	0	11	4
Checkpoint 8-9	0	2	1	3	2	4	2	5	7	0	2	2	1	5	2	4	17	25
Checkpoint 9-10	0	0	0	2	1	0	0	1	0	0	0	0	0	0	0	1	1	4
Checkpoint 10-11	0	0	0	1	0	0	0	0	2	1	0	1	1	0	1	1	4	4
Checkpoint 1-11	15	14	11	17	20	15	18	19	24	16	9	4	14	18	13	15	124	118

Abbreviations: QF, quarterfinal; SF, semi-final; F, Final

STUDIES I-III

Paper I

This paper is not included due to copyright avialable in
Physiology and Performance (IJSPP) 2018 ;Volum 14.(6) s. 788-795
https://doi.org/10.1123/ijspp.2018-0507 and http://hdl.handle.net/11250/2583767

Paper II

PLOS ONE

RESEARCH ARTICLE

The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition

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Citation: Haugnes P, Kocbach J, Talsnes RK, Noordhof D, Ettema G, Sandbakk Ø (2022) The influence of race tactics for performance in the heats of an international sprint cross-country skiing competition. PLoS ONE 17(12): e0278552. https://doi.org/10.1371/journal.pone.0278552

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

Received: June 15, 2022

Accepted: November 18, 2022

Published: December 9, 2022

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

Funding: The author(s) received no specific funding for this work.

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

Abstract

The purpose of this study was to examine the influence of race tactics for performance in the heats of an international sprint cross-country (XC) skiing competition in the classical style. Thirty elite male XC skiers (age: 24±3 years, sprint International Ski Federation [FIS] points: 61±27) performed a sprint time-trial (STT) followed by one to three 'knock-out' heats on a 1.7 km racecourse. An integrated GNSS/IMU system was used to determine position, sub-technique distribution and kinematics. Positioning was analysed using the television broadcast of the race. STT rank correlated positively with the final rank [(r_s (28) = .72, P = .001)]. The top-two finishers in each heat were on average ~3.8% slower in the heats compared to the STT (237.1±3.9 vs. 228.3±4.0 seconds, P = .001). On average, the skiers performed ~10 overtakings per 100 meters from the start to the last uphill segment but only ~3 overtakings per 100 meters in the last two segments in each heat. 93.8% of the top-two finishing skiers positioned themselves at top 2 before approaching the final uphill, in which the top-two finishers and the skiers ranked 3–4 were generally faster than those ranked 5–6 in the heats (both, P = .01). Here, top-four skiers employed 5.3% longer cycle lengths and 3.4% higher cycle rates in the diagonal sub-technique than skiers ranked 5–6 (all, P = .01). The present study demonstrates the importance of race tactics for performance in the heats of sprint XC skiing, in which the main performance-determining factors in the present racecourse were a front position when approaching the final uphill segment combined with the ability to ski fast in that segment. In general, this illustrates how accurate racecourse analyses may help skiers to optimize their race-individual race-strategies in the heats of sprint XC skiing competitions.

Introduction

An International Ski and Snowboard Federation (FIS) regulated sprint cross-country (XC) skiing competition consists of one to four ~3-minute races performed on varying terrain over a

1.0- to 1.8-km racecourse separated by ~15–60 minutes periods of recovery. The skiers employ different sub-techniques (gears) of the classical and skating styles, in which they continuously change between gears and adapt according to the terrain, speed, and race conditions [1, 2]. Sprint competitions begin with an individual qualifying sprint time-trial (STT), from which the thirty fastest skiers qualify for the subsequent 'knock-out' heats (i.e., five quarterfinals [QF], two semi-finals [SF], and one final [F]). In the heats, six skiers compete head-to-head using a knockout system where the top-two finishers in the QFs and SFs qualify for the subsequent heat along with the two fastest remaining skiers ('lucky losers'). Consequently, skiers in the heats need to pace and position themselves to reach a top-two finish and then recover rapidly to perform well in the subsequent heat. Hence, sprint XC skiing requires well-developed aerobic and anaerobic energy delivery capacities, strength, and speed abilities, as well as technical and tactical expertise [3–11].

In the individual STT, the skiers' pacing strategy (i.e., the individual's distribution of metabolic energy) is regulated according to their own racing template while aiming to optimise the overall time based on the given conditions [2, 12–20]. However, the main aim in the subsequent heats is not necessarily to produce the fastest time, but to finish ahead of other competitors and thereafter recover rapidly for the subsequent heat. In heats, the skiers' speed, positioning, and sub-technique selection depends on several factors additional to metabolic energy regulation, such as the other competitors' race strategies, the advantage of drafting behind competitors, and avoidance of accidents. These factors may influence the skiers' grade of fatigue, sprint abilities and position when reaching the finish sprint [21–27].

Thus far, only three recent studies have examined performance during the heats in sprint XC skiing [28–30]. Andersson et al. [29] found on average ~2.4% faster times in the heats than in the STT of a simulated skating sprint race, with most heat winners (61%) being positioned first already after the initial 30 meters of their respective heats. However, this simulated race monitored only a limited number of participants (twenty out of thirty male and fourteen out of thirty female skiers) with significant heterogeneity in performance level. Therefore, the fastest skiers were positioned first already from the start and could control the heats, unlike international sprint races where different types of race tactics are normally employed [11, 17]. In addition, Andersson et al. [29] classified sub-techniques and the corresponding kinematic patterns by using video recordings only in the finish sprint of the racecourse and in short uphill sections spanning 25–40 m, in which the few cycles analysed reduces the validity of their results. In two studies of Marsland et al. [28, 30], individual differences in pacing strategy, sub-technique selection, and related cycle characteristics were identified for female skiers over the entire racecourse of a classical sprint XC skiing race. However, there were too few competitors for the QFs to be held and only six out of twelve skiers were analysed. Consequently, the influence of pacing strategy and race tactics on performance in the heats of an actual sprint XC skiing race is not fully explored and therefore limits our current understanding of sprint XC skiing. This could be achieved by combining video analysis of positioning with the use of wearable sensor technology, allowing full-course analyses of speed and continuous detection of sub-technique selection and related kinematic patterns [1, 2, 19, 28, 30–44]. Therefore, the present study was designed to examine the influence of race tactics for performance in the heats of an international sprint cross-country (XC) skiing competition in the classical style.

Materials and methods

Participants

Thirty male XC skiers (age: 24±3 years, sprint FIS points: 61±27) that qualified for the knock-out heats an international FIS-regulated classical sprint XC skiing competition were selected for this study. The skiers' performance level ranged from Tier 3 (National Level) to Tier 5 (World-Class Level) as defined by McKay et al. [45]. The competition analysed was held at the start of the competitive season (mid-November) in Norway in 2017. The study was pre-approved by the Norwegian Centre for Research Data (NSD), and all skiers were fully informed about the nature of the study before they provided their written consent to participate.

Design

All skiers performed the individual qualifying STT followed by the knockout heats on a 1.7 km racecourse. First, we investigated how performance in the STT correlated with the final rank of the race. To determine the association between speed profiles, positioning, sub-technique selection and kinematics with performance in the heats, all skiers were monitored by an integrated GNSS/IMU system while the skiers' positioning in the heat was analysed using the television broadcast of the race.

In addition, we did two complementary analyses: 1) we examined the difference in speed profiles and sub-technique selection between the heats and the STT in seven pre-selected skiers with high performance level (age: 27±4 years, sprint FIS points: 33±25) and thereby large chances to qualify for the subsequent heats (see S1 Appendix and Fig 5), and 2) as an indication of the generalizability of our results, we compared the number of overtakings performed in the analysed competition (performed in 2017) with a comparable FIS-regulated classical sprint XC skiing competition in 2019 by male skiers of a similar performance level (age: 25±3 years, sprint FIS points: 57±40) (see S2 Appendix).

Instruments and materials

Position, speed, and movement data of all skiers were continuously measured using an integrated sensor device consisting of a global navigation satellite system (GNSS) and an inertial measurement unit (IMU) (Optimeye S5, Catapult Sports, Melbourne, Australia), using a sampling frequency of 10-Hz for GNSS data and 100-Hz for IMU data. GNSS lock was ensured by placing the sensor device in a clear outdoor space for a minimum of 10 minutes prior to the data collection to allow for the acquisition of satellite signals, and the sensor device was carried in a pocket in the upper part of the race bib. The sensor device has been validated for position, speed, and time analysis in XC skiing against a geodetic, multi-frequency receiver by Gløersen et al. [46], ensuring that the sensor device is able to reliably detect differences in performance in line with the research questions in the current study. The racecourse was measured using a high-end differential, multi-frequency and multi-GNSS receiver (Alpha-G3T, Javad, San Jose, CA, USA) to provide a valid racecourse and elevation profile. The skiers' data were adapted to the standard racecourse for analysis of sub-technique selection and kinematic pattern. The sensor device failed to register GPS-data and caused missing data in one case (N = 1). One skier broke his pole twice in the same heat, and another skier fell, which caused missing data in two other cases (N = 2).

Video analysis of positioning and accidents (obstruction, fall, pole break) were performed by using publicly available television broadcast of the Norwegian Broadcasting Corporation (NRK). For this analysis, the racecourse was separated into 11 segments (S1-S11) using 11 checkpoints according to terrain topography (Fig 1). Accordingly, these segments were grouped in the analysis of comparing racing time in the STT with the heats, where the various phases of the race were divided into the following groups: S1-S3, S4-S5, S6-S7, S8-S9, and S10-S11. The racecourse was 1720 m (consisting of 1 lap) and uphill, flat, and downhill made up 31%, 17%, and 52% of the total racecourse, respectively. The racecourse consisted of 3 uphill segments (S4, S6, and S9) with mean inclines of ~8%, 9%, and 9% and length of 280, 90, and 160 m; 3 flat segments (S1, S7, and S11) with length of 80, 110 and 100 m; 5 downhill

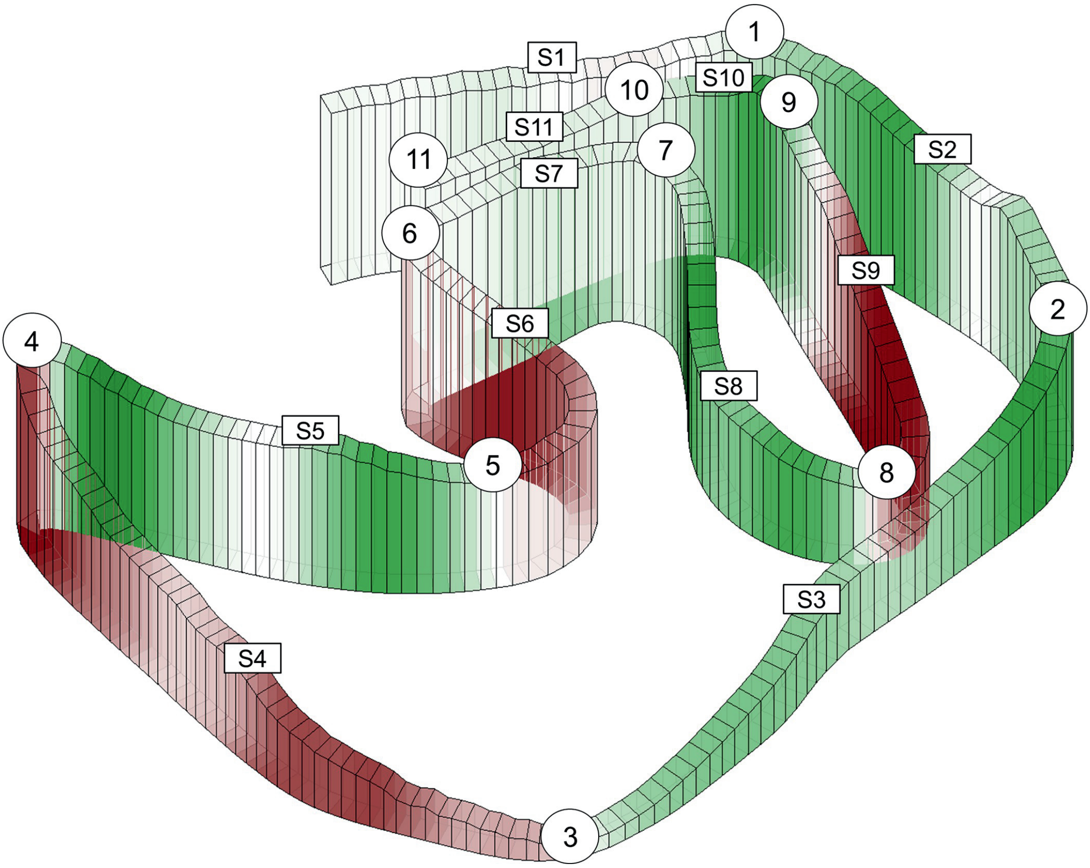

Fig 1. Racecourse. Three-dimensional illustration of the 1.7-km racecourse examined in the current study where the 11 segments (S1-S11) and 11 checkpoints are shown along the racecourse from start to finish. The colours represent terrain; uphill (red), flat (white), downhill (green), respectively.

https://doi.org/10.1371/journal.pone.0278552.g001

segments (S2, S3, S5, S8, and S10) with mean slopes of approximately -4%, -5%, -3%, -7%, and -4% and length of 160, 300, 190, 170 and 80 m. The maximal elevation difference was 21 m with a total climb of 44 m for the entire racecourse. The last uphill in the racecourse in segment S9 consisted of a technique zone, where only the diagonal stride (DIA) was allowed to use. Obstruction was classified according to the following classification criteria: Skier A suffered loss of speed and/or rank due to skier B performing track change irregularly. Prior to the race, the skiers performed self-selected warm-up procedures according to their own individual program. All skiers used ski equipment optimised for the specific athlete's racing preferences, including poles, boots, and skis. All ski-base preparations, including grinds, structure, and waxing, were optimised for the snow conditions on the competition day by the team of each individual. The weather conditions were stable throughout the entire day, with light wind, partly cloudy, air and snow temperature of -3˚C, ~84% humidity, and atmospheric pressure of ~901.6 hPa. The racecourse was covered by hard-packed artificial snow, which had been machine-prepared the morning of the race day.

Sub-technique classifications

The sub-technique classification was undertaken using a K-Nearest Neighbour algorithm as previously described by Solli et al. [44]. The algorithm was trained on nine skiers for the racecourse used in this competition and seven skiers for another racecourse, and subsequently tested on three other skiers with a per-distance classification accuracy of 96% for the complete racecourse in this competition. The classifications were also examined visually by comparing a graphical representation of filtered accelerometer and gyroscope signals with those typical for the various sub-techniques. Any errors in the automated classification were subsequently corrected based on the visual inspection. The error for GPS-measured time vs. the official time in the race was 0.05±0.18 seconds. The sub-techniques were classified as diagonal (DIA), double poling with a kick (DK), double poling (DP) and Other, the latter including tuck (TCK) and various turning techniques (TRN). The cycles were automatically segmented based on peak detection of Gaussian low pass filtered data from one axis of the gyroscope. Cycle length (CL) was calculated as the average speed multiplied by the cycle time (CT) and the cycle rate (CR) was calculated as the reciprocal of cycle time.

Statistical analysis

All data are presented as mean ± standard deviation (SD), unless otherwise stated. Shapiro-Wilk test, visual inspection of Q-Q plots, and comparison of histograms were used to assess normality. Levene's test was used to assess the homogeneity of variances. The Spearman rank-order correlation coefficient was performed to assess the relationship between the STT rank and the final rank. A paired-samples t-test was used to determine whether there was a statistically significant difference between the race time in STT and the heats for the top-two performers in each heat, and race time in STT vs. the heats in different segments for seven skiers analysed in detail (see S1 Appendix). Positioning for heat winners and top-two finishers were explored. During the heats, the percentage of heat winners' and top-two finishers' checkpoint positioning (i.e., rank 1–6) was determined. Positioning of all skiers was examined by assessing the relationship between intermediate rankings and final rankings by using Kendall tau-b correlations. To assess the repeatability of overtakings between 2017 vs. 2019 we used the intraclass correlation coefficient (ICC), a two-way random-effect model based on single measurements and absolute agreement. Percentage difference equals the absolute value of the change in value, divided by the average of the 2 number, all multiplied by 100. A one-way ANOVA was conducted to determine if speed and kinematics for DIA in S9 were different for groups with different final ranking (heat rank 1–2, heat rank 3–4, heat rank 5–6). Tukey post-hoc test was used to assess the significance of differences between groups. The magnitude of the correlation coefficients and effect sizes were interpreted as following: 0.0–0.1, trivial; 0.1–0.3, small; 0.3–0.5 moderate; 0.5–07, large; 0.7–0.9, very large; 0.9–1.0, nearly perfect [47]. The statistical significance level was set at $\alpha<0.05$. All statistical analyses were processed using STATA 16.0 software (Stata Corporation, College Station, TX, USA) and Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA).

Results

The relationship between STT rank and the overall ranking

There was a large positive correlation between STT rank and the final rank of the race, [$r_s(28) = .72$, $P = .001$].

Table 1. Skiing time for the top-two finishers and number of incidents during a 1.7-km classical sprint cross-country skiing race for elite male skiers. Presented as absolute values [N = 16].

Variable	QF 1	QF 2	QF 3	QF 4	QF 5	SF 1	SF 2	F
Heat rank 1 (s)	236.00	235.00	238.10	237.90	243.90	233.20	232.40	230.40
Heat rank 2 (s)	236.50	235.40	238.70	238.20	244.10	233.40	232.40	231.50
Heat rank 1 (%STT_{top1})	6.9	6.5	7.7	7.6	9.9	5.8	5.4	4.6
Heat rank 2 (%STT_{top1})	7.1	6.6	7.9	7.7	10.0	5.8	5.4	5.1
Obstruction	3	2	1	3	0	3	1	1
Fall	0	0	0	1	0	0	0	0
Pole break	0	0	0	0	2	0	0	0
Yellow card	0	0	0	0	0	0	0	0

Abbreviations: STT, time-trial; QF, quarterfinal; SF, semi-final; F, Final; %STT_{top1}, percentage of the sprint time-trial winner time.

https://doi.org/10.1371/journal.pone.0278552.t001

Speed, time, positioning, and technique distribution

Skiing times for the top-two finishers and number of incidents (obstruction, fall, pole break, yellow card) are shown in Table 1. Top-two finishers were on average ~3.8% slower in the heats than in the STT [average heat time: 237.1±3.9 vs. STT: 228.3±4.0 (s)], with the difference being significant [$t(9)$ = -6.578, P = .001, d = 2.22]. The number of overtakings on the different segments included in total 124 overtakings during the heats (i.e., ~16 overtakings in each heat). By adjusting overtakings for segment length, it becomes clear that the skiers performed ~10 overtakings per 100 meters from the start to the final uphill segment (S2 to S9), and only ~3 per 100 m on the two last segments (S10 to S11). Most overtakings were observed in the longest uphills (S4 and S9), although many overtakings were also performed in all types of segment types (i.e., uphill, downhill, and undulating terrain).

The positioning of heat winners and top-two finishers at different checkpoints during the racecourse are presented in Table 2. Here, 75% of those who won the heats were positioned first in the final uphill segment, whereas 93.8% of the top-two finishers were being positioned first or second on this segment. The relationship between intermediate ranks and final ranks during the heats is presented in Fig 2. As expected, the strength of the correlation increased segment-by-segment throughout the race and was strongest at the end of the race.

Table 2. Percentage of heat winners (left part) and top-two finishers (right part) positioned at rank 1–6 at the 11 checkpoints during the heats of a 1.7-km classical sprint cross-country skiing race for elite male skiers. Presented as percentages [N = 16].

Variable	Heat winner						Top 2-finishers					
Checkpoints 1–11	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**
1. Out of stadium	25.0%	12.5%	25.0%	12.5%	12.5%	12.5%	12.5%	31.3%	18.8%	18.8%	6.3%	12.5%
2. First downhill	25.0%	12.5%	25.0%	12.5%	12.5%	12.5%	12.5%	31.3%	12.5%	18.8%	6.3%	18.8%
3. End of first downhill	50.0%	0.0%	12.5%	25.0%	12.5%	0.0%	31.3%	18.8%	12.5%	18.8%	12.5%	6.3%
4. End of first uphill	37.5%	12.5%	0.0%	25.0%	25.0%	0.0%	31.3%	25.0%	6.3%	12.5%	18.8%	6.3%
5. End of second downhill	37.5%	12.5%	37.5%	0.0%	12.5%	0.0%	31.3%	25.0%	25.0%	6.3%	6.3%	0.0%
6. End of second uphill	50.0%	12.5%	25.0%	0.0%	12.5%	0.0%	43.7%	25.0%	18.8%	6.3%	6.3%	0.0%
7. Before third downhill	75.0%	0.0%	12.5%	0.0%	0.0%	12.5%	50.0%	12.5%	31.3%	0.0%	0.0%	6.3%
8. End of third downhill	75.0%	0.0%	12.5%	0.0%	0.0%	12.5%	50.0%	25.0%	18.8%	0.0%	0.0%	6.3%
9. End of third uphill	75.0%	12.5%	12.5%	0.0%	0.0%	0.0%	43.8%	50.0%	6.3%	0.0%	0.0%	0.0%
10. Before the finish-sprint	75.0%	12.5%	12.5%	0.0%	0.0%	0.0%	43.8%	50.0%	6.3%	0.0%	0.0%	0.0%
11. Finish	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%	50.0%	0.0%	0.0%	0.0%	0.0%

Checkpoint 11 Finish: All heat winners were ranked 1, whereas top 2-finishers were either ranked 1 or 2.

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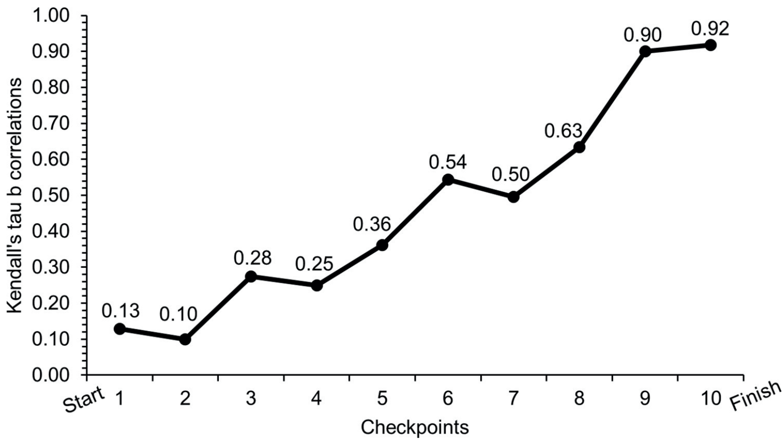

Fig 2. Kendall's tau-b correlations. The relationship between intermediate ranks and final rank during the heats of a classical sprint cross-country skiing race for elite male skiers [N = 30].

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Fig 3 shows the average time behind the leader in each segment, as well as speed, and positioning for all heats. Here, all skiers were within 4 seconds behind the leader of the group until the final uphill in segment S9 where heat rank 1–4 were generally faster than heat rank 5–6 who were unable to keep up the pace and/or gave up.

The distribution of sub-techniques in relation to the racecourse for all skiers during QFs, SFs and F are shown in Fig 4. Here, the skiers are presented according to the order of ranking in each heat, and all skiers demonstrated similar sub-technique selection along the racecourse. The percentage use of different sub-techniques in relation to the distance for the STT (N = 7) and heats (N = 28) is shown in Fig 5. Here, you can see that there is no statistical difference in the use of sub-technique selection.

Speed, CL, and CR for DIA in the last uphill segment (S9) are shown in Table 3. Here, skiers were grouped according to their overall rankings; heat rank 1–2 (N = 16), heat rank 3–4 (N = 16) and heat rank 5–6 (N = 13). The segment speed differed significantly between groups [$F(2,42) = 32.32$, $P = .001$, $\omega2 = 0.58$], with the skiers ranked 1–2 and 3–4 showing significantly higher speed than those ranked 5–6 (both, $P = .001$), while the corresponding difference between heat rank 1–2 and 3–4 did not differ ($P = .600$). CL differed significantly between groups, [$F(2,42) = 7.35$, $P = .002$, $\omega2 = 0.22$], with the skiers having heat rank 1–2 and 3–4 showing a significantly longer CL than those ranked 5–6 ($P = .003$ and .007). In contrast, the difference in CL between heat rank 1–2 and 3–4 did not differ ($P = .936$). CR differed significantly between groups, [$F(2,42) = 7.02$, $P = .002$, $\omega2 = 0.21$], with the skiers having heat rank 1–2 and 3–4 showing a significantly higher CR than those ranked 5–6 ($P = .003$ and .012), while the difference between heat rank 1–2 and 3–4 was non-significant ($P = .838$).

Discussion

The purpose of this study was to examine the influence of race tactics for heat performance during an international sprint XC skiing race in the classical style. The main findings were as follows: 1) a large correlation between STT rank and the final rank of the race was found; 2) the top-two finishers in each heat were on average ~3.8% slower in the heats compared to the STT, a difference that, based on the seven skiers examined in detail (S1 Appendix), appeared

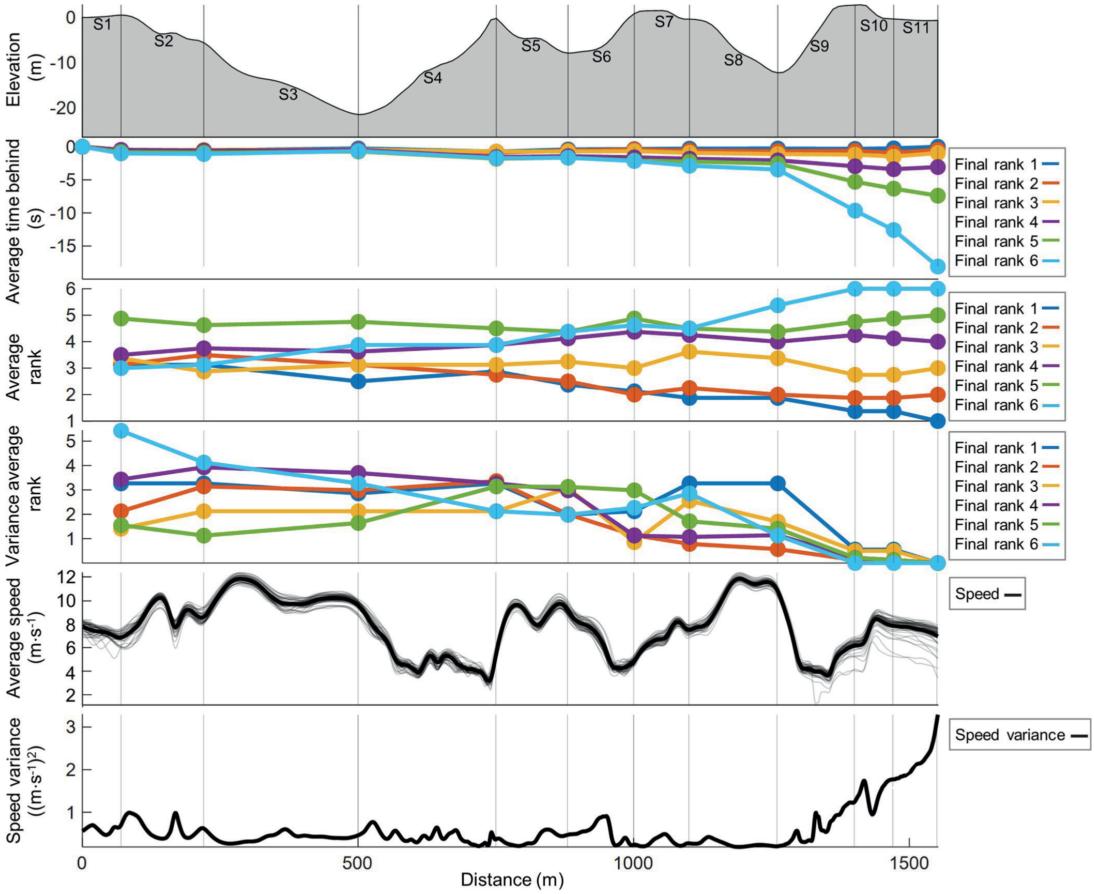

Fig 3. Time behind, speed, and positioning. The average time behind the winner, intermediate rankings, and skiing speed across the racecourse in 11 segments (S1-S11) during the heats of a classical sprint cross-country skiing race for elite male skiers [N = 29 time and speed, N = 30 positioning].

https://doi.org/10.1371/journal.pone.0278552.g003

during the initial segments of the heats; 3) on average, ~16 overtakings occurred in each heat, with a clear reduction in number of overtakings per 100 m in the two last segments; 4) 93.8% of the top-two finishing skiers positioned themselves on 1st or 2nd place when approaching the final uphill, in which the top-two finishers and the skiers ranked 3–4 were generally faster than the skiers ranked 5–6 in the heats, by employing 5.3% longer CL and 3.4% higher CR in the DIA sub-technique; and 5) we observed relatively similar sub-technique selection across skiers within and between heats.

While race tactics have previously been shown as an important performance determinant in other endurance sports such as cycling [48–50], middle-distance running [51–53], and short-track speed skating [54–56], this is the first study to examine race tactics in an actual sprint XC skiing race. We found a significantly large correlation between STT rank and the final rank of the race. This finding is in line with Spencer et al. [8], who reported moderate to very large correlations between STT rank and final rank in both classical and skating races for

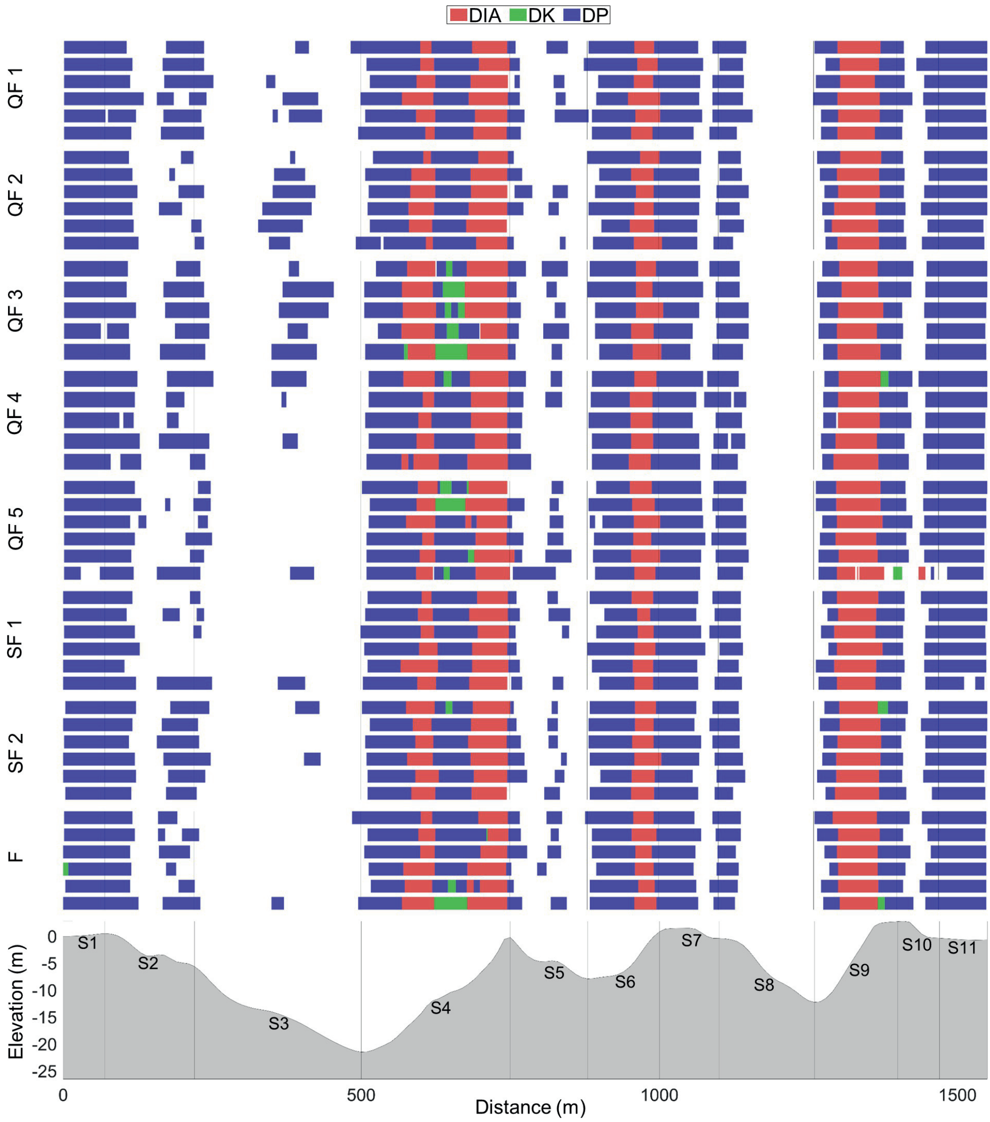

Fig 4. Individual sub-technique selection. The individual use of sub-techniques (diagonal stride [DIA], double poling with a kick [DK], double poling [DP]) and [Other] including tuck and turning techniques) across the racecourse in 11 segments (S1-S11) during the heats of a classical sprint cross-country skiing race for elite male skiers. The skiers are presented according to the order of ranking from top 1st to bottom 6th [N = 28].

https://doi.org/10.1371/journal.pone.0278552.g004

both men and women. Nevertheless, the correlations shows that a relatively large portion of the variance in final rank was not explained by STT performance, which demonstrates the importance of performance in the heats where race tactics and the ability to master an entire day comprising multiple heats are important performance-determinants.

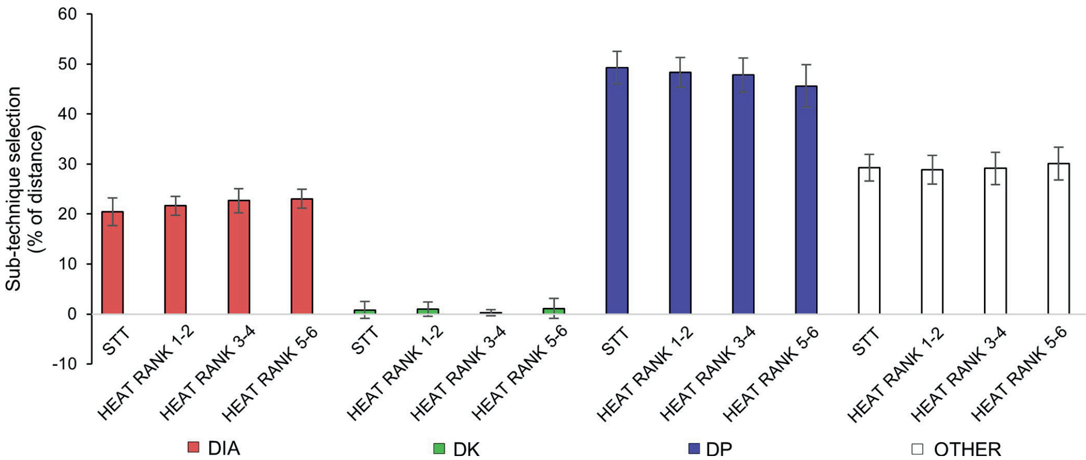

Fig 5. Sub-technique selection in relation to distance. The percentage use of sub-techniques (diagonal stride [DIA], double poling with a kick [DK], double poling [DP]) and ([Other] including tuck and turning techniques) in relation to distance across the racecourse during the sprint time-trial and heats of a classical sprint cross-country skiing race for elite male skiers. Error bars indicate SD [N = 28].

https://doi.org/10.1371/journal.pone.0278552.g005

In the study by Andersson et al. [29], skiers were found to be ~2.4% faster in the heats than in the STT, with two-thirds of the heat winners being positioned first already after the initial segment of the race. These results are in contrast with the results of the current study, where the skiers were on average ~3.8% slower in the heats than in the STT, with 50% of the heat winners being positioned first after one-third of the heat, but with substantial changes in positioning throughout the remaining part of the course. The reason for this difference might be explained by the high degree of heterogeneity in performance level (sprint FIS points for men and women: 87±42 and 90±53) in the previous study by Andersson et al. [29], while our study included a more homogenous group of skiers. As a result, one can assume that the heat winners in Andersson et al. [29] were motivated to finish as top two in the relegation system and were able to control the heat from the leader position due to the large difference in performance level. In contrast, compared with the individually optimised pacing strategy in the STT, the skiers in our study chose to ski close to the leader of the group from start until the final uphill segment to position themselves strategically. This resulted in slower speed at the beginning of the heats compared to the STT, whereas this speed difference gradually levelled out and the skiers did not differ in speed from S6 to the end of the racecourse. The lower speed in the first part of the racecourse during heats likely enabled skiers to change position more frequently, with overtakings being performed in all types of terrain segments. However, most

Table 3. Cycle characteristics in the diagonal sub-technique during the final uphill segment in a 1.7-km classical sprint cross-country skiing race for elite male skiers. Values are mean ± SD [N = 27].

Variable	Heat rank 1–2	Heat rank 3–4	Heat rank 5–6
Speed ($m \cdot s^{-1}$)	4.15 ± 0.12^{c}	4.08 ± 0.18^{c}	3.62 ± 0.25^{a,b}
CL (m)	1.45 ± 0.08^{c}	1.44 ± 0.08^{c}	1.35 ± 0.07^{a,b}
CR (Hz)	1.43 ± 0.05^{c}	1.42 ± 0.06^{c}	1.34 ± 0.10^{a,b}

Abbreviations: CL, cycle length; CR, cycle rate. The letters indicate statistically differences from heat rank 1–2 (a), heat rank 3–4 (b), or heat rank 5–6 (c) ($P < 0.05$).

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overtakings were observed in the two longest uphill segments (S4 and S9). Accordingly, positioning at the checkpoint at the start of the final uphill segment was a key determinant of heat performance, in which 93.8% of the top-two finishers positioned themselves on 1st or 2nd place, although one skier was able to win the race by skiing from last position in the beginning of the uphill. The highest ranked skiers (rankings 1–4) were generally faster in this uphill segment (S9) by utilizing longer CL and higher CR in the DIA sub-technique compared to the skiers ranked 5–6. However, even if the final uphill segment was crucial for heat performance in this study, different racecourses and snow conditions might affect the skier's race tactics, and every race (and skier) will, to some degree, require different tactical decisions [57, 58], as exemplified for both sexes in the study by Andersson et al. [29].

Although better-performing skiers produced longer CL and higher CR in DIA in the last uphill segment, all skiers selected similar sub-techniques during the race as seen with both the individual use of sub-techniques and the percentage use of sub-techniques in relation to distance (Figs 4 and 5). These findings are, however, in contrast to those of Marsland et al. [30] who found larger variations in sub-technique selection during a classical sprint race. A plausible explanation for this might be the differences in topography and race strategy between the two studies. In addition, the fact that the skiers in the previous study by Marsland et al. [30] were women while our study sample included men only may to some degree explain this difference in sub-technique selection as shown previously in a classical distance race [44]. Furthermore, the skiers in the heats in sprint XC skiing are often grouped during the race, and the skiers in our study mainly used the same sub-technique as the skiers in front. Hence, the racecourse together with the sub-technique selection employed by the leader of the group will often influence the variation in technique distribution in the heats. Therefore, future research should investigate skiers' technique distribution and corresponding kinematic patterns in different races and whether a larger variation in sub-technique usage can be expected in female compared to male skiers.

Whether the findings of this study are generalisable or would differ between sexes, environmental conditions, and racing styles are topics for further investigations. However, the high ICC (.77, $P = .004$) found between overtakings in the 2017 competition and the repeated competition two years later (see S1 Table in S2 Appendix), indicates that similar race tactics identified in this study are to be expected in other races performed on the same racecourse by skiers of a similar performance level if the environmental conditions are comparable.

Overall, the interpretation of the most-optimal strategies identified in this study is based on the best skiers self-selected tactics, which are adopted not only for the given racecourse and snow conditions but also according to their opponents and the individual skier's strengths and weaknesses. Further exploration of speed profiles together with the number of overtakings and where these take place would contribute to better understanding of the underlying mechanisms of race tactics. Here, the utilization of sensor technology and the classification of intermediate rankings along the racecourse would increase the validity of the measurements. Therefore, we suggest that future studies should further explore the effectiveness and metabolic cost of typical elements used as race tactics during sprint XC skiing. Such insights would allow a deeper insight in the underlying mechanisms of race tactics in sprint XC skiing and could potentially help practitioners to optimise race strategies for different race formats.

Conclusions

The findings in this study demonstrate that race tactics is an important determinant of heat performance in sprint XC skiing. Race times in the heats were longer than the corresponding times for the STT, which can be explained by lower speed in the beginning of each heat, thereby allowing for multiple overtakings in these segments. There was a clear reduction in the number of overtakings after the final uphill segment, where most top-two finishers were already positioned first or second. Accordingly, a top-ranked position (i.e., 1^{st} or 2^{nd} place) before the final uphill segment, in combination with higher uphill DIA speed by utilising longer CL and higher CR, were the main performance determinants in the heats. However, each racecourse is different, and the practical implications are that accurate racecourse analysis combined with an understanding of each skier's strengths and weaknesses may be crucial factors for success in the heats of sprint XC skiing.

Supporting information

S1 Appendix. The difference in speed profile between the heats and the sprint time-trial in seven pre-selected skiers.
(PDF)

S2 Appendix. The number of overtakings during a repeated classical sprint cross-country skiing race for elite male skiers performed in the same racecourse in 2017 and 2019.
(PDF)

S1 File. Data and analyses conduced in this study.
(XLSX)

Acknowledgments

The authors would first like to thank the skiers and their coaches for their participation, enthusiasm, and cooperation. We would also like to thank Matthias Felix Gilgien and his colleagues at the Norwegian School of Sport Sciences for providing us with DGPS-data of the racecourse. Finally, we would like to thank Øyvind Salvesen at the Norwegian University of Science and Technology (NTNU) for helpful discussions about the statistics in this study.

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Paper III

PLOS ONE

RESEARCH ARTICLE

The influence of tactical positioning on performance in sprint cross-country skiing

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Abstract

The purpose of this study was to examine the influence of tactical positioning on performance in the heats of sprint cross-country (XC) skiing among men and women and the consistency of overtaking events over repeated competitions on the same racecourse. Thirty male and thirty female elite to world-class level skiers within each competition [(sprint International Ski and Snowboard Federation (FIS) points: 40 ± 21 vs. 35 ± 24)] performed two repeated world-cup competitions at four different venues (two in the classical and two in the skating style) between 2017 and 2020. The intermediate rankings at five checkpoints were analysed using television broadcasts of the competitions. Sprint time-trial (STT) rank correlated positively with the final rank for the seven men's (ρ = .54-.82, $P < .01$) and the eight women's (ρ = .40-.80, $P < .05$) competitions, while one of the classical competitions for males did not correlate significantly ($P = .23$). The strength of the correlation coefficients between intermediate ranks and final ranks during the heats increased gradually from the first to the last checkpoint among both sexes in the classical style (τ = ~0.26 to ~0.70) and in the skating style (τ = ~0.22 to ~0.82), in which the majority of performance-variance was decided before the start of the finish sprint. For both sexes, ~20 and 16 overtaking events were observed in each heat for the classical and skating style, respectively. There was a significant sex-difference in the number of overtaking events in one out of the 16 competitions ($P < .01$), but no differences across seasons for any competition ($P = .051–796$). Overall, this study showed the importance of tactical positioning for performance in sprint XC skiing, with the number of overtaking events being relatively consistent for competitions performed on the same racecourse.

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Citation: Haugnes P, Kocbach J, Noordhof D, Talsnes RK, Ettema G, Sandbakk Ø (2023) The influence of tactical positioning on performance in sprint cross-country skiing. PLoS ONE 18(6): e0287717. https://doi.org/10.1371/journal.pone.0287717

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

Received: December 9, 2022

Accepted: June 11, 2023

Published: June 23, 2023

Data Availability Statement: All relevant data are within the manuscript and its Supporting information files.

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

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

Introduction

A sprint cross-country (XC) skiing competition involves a qualifying sprint time-trial (STT), from which the thirty fastest skiers qualify for the subsequent knockout heats (i.e., five quarter-finals [QFs], two semi-finals [SFs], and one final [F]). Here, six skiers in each heat compete against each other for the top-two ranks that qualify for the next round along with the two fastest overall times. The ~3-minute races are performed on varying terrain over a 1.0–1.8 km racecourse, in which the skiers continuously change between sub-techniques (gears) and adapt according to topography and external conditions, such as friction, temperature and wind. The four races within each sprint competition are separated by ~15 to 60-minute breaks, where the ability to recover rapidly is important for performance in the subsequent heats [1–13]. Moderate to large correlations between STT rank and final rank of a sprint competition have been reported [8, 14], and Spencer et al. [8] found a stronger correlation for men than for women, particularly evident in the skating style.

The skiers' race tactics (including tactical positioning) is regarded particularly important for performance since the final rank in each heat determines whether you advance to the subsequent heat and possibly win the competition. Research on XC skiing mass-start competitions [15] indicate that the positioning of a skier in the pack can both positively and negatively influence energy expenditure and performance. Skiing at the back of the pack may reduce air drag [16] and ski-snow friction [17–19] when compared to skiing at the front. However, this strategy also carries a trade-off, as being too far behind increases the risk of accidents and the accordion effect, which may require more energy for subsequent overtaking events. Although the number of skiers is lower in sprint compared to mass-start events, the same aspects are expected to be of importance during a heat in sprint XC skiing. Here, tactical positioning and overtaking events are crucial, as competitors not only have to determine their own tactical behaviour but must also consider the actions of their opponents. Previously, Andersson et al. [13] found that most heat winners (61%) in a simulated skating competition were leading already after the initial 30 meters of their respective heats. Moreover, it was shown that the strength of the correlations between intermediate rankings at given checkpoints and the final rank ranged between 0.51–0.84, with increased strength towards the finish line. In contrast, Haugnes et al. [14] reported that the best performers in a male classical sprint competition awaited to position themselves at the front of the heat until approaching the final uphill, after which a clear reduction in the number of overtaking events were seen. However, whether these findings differ between the classical and skating style, racecourses, and sexes has not yet been investigated.

Since the period investigated by Spencer et al. [8] and Andersson et al. [13], sprint XC skiing has evolved, for example by more women being specialized in sprint and both sexes more often competing on the same racecourse. Accordingly, there is a need for a better understanding and more updated information related to tactical positioning in sprint XC skiing. In this context, knowledge about the consistency of the number and location of overtaking events, when a competition is repeated on the same racecourse (and comparable conditions) is of interest for understanding the repeatability of "heat behaviour" which also has practical relevance for subsequent racecourse preparations.

Therefore, the purpose of the present study was to examine the influence of tactical positioning on performance in the heats of sprint XC skiing among men and women and the consistency of overtaking events over repeated competitions on the same racecourse.

Methods

Design and participants

Thirty male and thirty female XC skiers in each competition, who performed two repeated competitions at four different venues (two in the classical and two in the skating style; in total eight competitions for each sex) between the seasons 2017 and 2020 were analysed. The skiers' performance level [(sprint International Ski and Snowboard Federation (FIS) points: 40 ± 21 vs. 35 ± 24)] ranged from Tier 4 (elite/international level) to Tier 5 (world-class level) as defined by McKay et al. [20]. Given data are in the public domain, written consent from athletes and ethical approval was not required.

Measurements

The inclusion criteria for the analysed competitions in this study were that the competitions needed to be held before the 2019/2020 season with the same style, racecourse, and comparable environmental conditions. A total of 15 competitions were assessed for eligibility and 4 competitions were included in the analysis. The competitions at locations A, B, C, and D were performed in the 2017/2018 or 2018/2019 season and then repeated on the same racecourse during the 2019/2020 season. Official competition results were downloaded from the publicly available FIS online database (www.fis-ski.com). Video analysis of tactical positioning and incidents (obstruction, fall, pole break) were obtained by publicly available television broadcast (Norwegian Broadcasting Corporation [NRK] and TV 2 Group). For these analyses, the racecourses were separated into 5 segments (S1-S5) using 5 checkpoints based on terrain topography and classified according to the following criteria; out of stadium (checkpoint 1), crucial parts e.g., major uphill (checkpoint 2 and 3), before the finish sprint (checkpoint 4), and finish (checkpoint 5). Obstruction was classified according to the following classification criteria; skier A suffered loss of speed and/or rank due to skier B performing a non-regulatory track change.

Statistical analysis

All data are presented as mean ± standard deviation (SD), unless otherwise stated. Shapiro-Wilk test, visual inspection of Q-Q plots, and comparison of histograms were used to assess normality. In cases of non-normally distributed data, a nonparametric alternative was used. The Spearman rank-order correlation coefficient was performed to assess the relationship between the STT rank and the final rank. Tactical positioning for heat winners was explored. During the heats, the percentage of heat winners' checkpoint positioning (i.e., rank 1–6) was determined. Positioning of all skiers was examined by assessing the relationship between intermediate rankings and final rankings by using Kendall tau-b correlations. A two-way mixed ANOVA was conducted to determine whether there was a statistically significant mean difference in overtaking events between men and women (between group comparison) on the same racecourse between seasons (within subject comparison). Levene's test was used to assess the homogeneity of variances. The magnitude of the correlation coefficients and effect sizes was interpreted as follows: 0.0–0.1, trivial; 0.1–0.3, small; 0.3–0.5 moderate; 0.5–07, large; 0.7–0.9, very large; 0.9–1.0, nearly perfect [21]. The statistical significance level was set at $\alpha<0.05$. All statistical analyses were performed using STATA 16.0 software (Stata Corporation, College Station, TX, USA) and Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA).

Results

The relationship between STT rank and the overall ranking

There were large positive correlations between STT rank and the final rank for male skiers both in the competitions using the classical (ρ = .65-.82, all $P < .01$) and skating styles (ρ = .54-.82, all $P < .01$), except for the 2019–2020 season in the classical competition A ($P = .23$). For the female skiers, moderate to large positive correlations were found between STT rank and the final rank in the classical style (ρ = .40-.78, $P < .05$) and large positive correlations in the skating style (ρ = .57-.80, all $P < .01$).

External conditions, time, and positioning

Overview of topography, weather, snow temperature, performance level, and number of incidents for all competitions analysed in this study are shown in Table 1. The total number of overtaking events for the competitions are shown in Fig 1, and the number of overtaking events on the different segments are shown in Fig 2. For both sexes, an average of 20 and 16 overtaking events were observed in each heat for the classical and skating style, respectively.

There were no significant interactions between sex and seasons on overtaking events in any of the competitions (P = .086–0.91). No significant differences in the number of overtaking events were found across seasons for any of the competitions (P = .051-.796). However, there was a significant difference in the number of overtaking events between sexes for competition A (P = 0.004), but not for competition B-D (P = .692-.849). See S1 Appendix for more information.

The heat winner's positions are presented in Table 2. Of the heat winners, ~53% of men and ~69% of women in the classical style, and ~63% of men and ~75% of women in the skating style, were positioned first in the heat at the last checkpoint before the start of the finish sprint. Of those ranked among the top-two at the finish, 31–44% were outside the top-two when leaving the stadium (i.e., checkpoint 1), while 34–44% of the heat winners were leading when leaving the stadium. The relationship between intermediate ranks at given checkpoints and final ranks for all skiers during the heats are presented in Fig 3. The average correlation (τ) for men ranged from 0.24 to 0.70 in the classical style and 0.20 to 0.84 in the skating style, whereas the average correlation for women ranged from 0.28 to 0.70 in the classical style and 0.23 to 0.81 in the skating style.

Discussion

The purpose of this study was to examine the influence of tactical positioning on performance in the heats of sprint cross-country (XC) skiing among men and women and the consistency of overtaking events over repeated competitions on the same racecourse. The main findings were as follows: 1) the moderate to large correlations between STT rank and final ranks found for most competitions were comparable between styles and sexes; 2) the strength of the correlation coefficients between intermediate ranks and final ranks during the heats gradually increased towards the last checkpoint before the finish sprint for both styles and sexes, with 94% in the classical style and 100% in the skating style being ranked top-two before the finish sprint; 3) for both sexes, ~20 overtaking events in the classical and ~16 overtaking events in the skating style were observed in each heat; 4) the number of overtaking events were consistent i.e., there were no significant differences between seasons for competitions organized on the same type of racecourse under comparable racing conditions.

As previously shown by Spencer et al. [8] and Haugnes et al. [14], moderate to large correlations between STT rank and final rank among both sexes were found for most competitions. However, in contrast to Spencer et al. [8], who found stronger correlations for women than for men in the classical style, such sex-difference was not evident in the present study. This may be explained by a more homogeneous performance level among women in the present study compared to the study of Spencer et al. [8], and that both sexes are now more often competing on the same racecourse. The strength of the correlations shows that a large portion of the variance could not be explained by performance in the STT, meaning that additional factors play a role for performance in the heats such as race tactics and the ability to recover between heats during the competition day. Therefore, future studies should investigate the relationship between recovery and heat performance since the highest ranked

Table 1. Overview of two repeated sprint cross-country skiing competitions held at four different venues (two classical and two skating). Presented as absolute values [N = 30 male and N = 30 female skiers within each of the eight competitions in this study].

Variable	Competition A classical				Competition B skating				Competition C skating				Competition D classical			
	Women1st yr	Men 1st yr	Women 2nd yr	Men 2nd yr	Women 1st yr	Men 1st yr	Women 2nd yr	Men 2nd yr	Women 1st yr	Men 1st yr	Women 2nd yr	Men 2nd yr	Women 1st yr	Men 1st yr	Women 2nd yr	Men 2nd yr
FIS (sprint points)	34 ± 24	42 ± 24	39 ± 26	40 ± 23	31 ± 25	43 ± 21	41 ± 26	37 ± 19	40 ± 25	46 ± 23	43 ± 27	40 ± 19	27 ± 14	38 ± 21	30 ± 18	35 ± 18
Air temp (˚C)	-0.5	-0.6	-4.0	-4.0	-1.9	-1.9	-2.0	-2.0	0.8	0.8	2.7	2.7	0.7	0.8	0.5	0.0
Snow temp (˚C)	-2.6	-2.5	-2.6	-2.6	-2.8	-2.8	-1.8	-1.8	0.2	0.3	-2.6	-2.6	-1.4	-1.2	-1.3	-1.3
Distance (m)	1400	1400	1400	1400	1500	1500	1500	1500	1500	1500	1500	1500	1214	1214	1200	1200
HD (m)	23	23	23	23	18	18	18	18	20	20	25	25	25	25	24	24
MC (m)	22	22	22	22	12	12	12	12	16	16	22	22	23	23	21	21
TC (m)	43	43	43	43	46	46	46	46	40	40	54	54	36	36	45	45
Laps (n)	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
Pole breaks (n)	0	1	0	1	1	2	0	1	2	0	1	1	0	0	0	0
Falls (n)	1	0	0	0	1	2	2	0	2	0	3	3	1	1	0	2
Obstructions (n)	3	3	4	0	1	2	6	4	1	1	1	6	9	4	4	3
Yellow cards (n)	4	2	0	2	0	0	1	1	0	0	0	0	0	3	3	0

Abbreviations: HD, height difference; MC, max climb; TC, total climb

https://doi.org/10.1371/journal.pone.0287717.t001

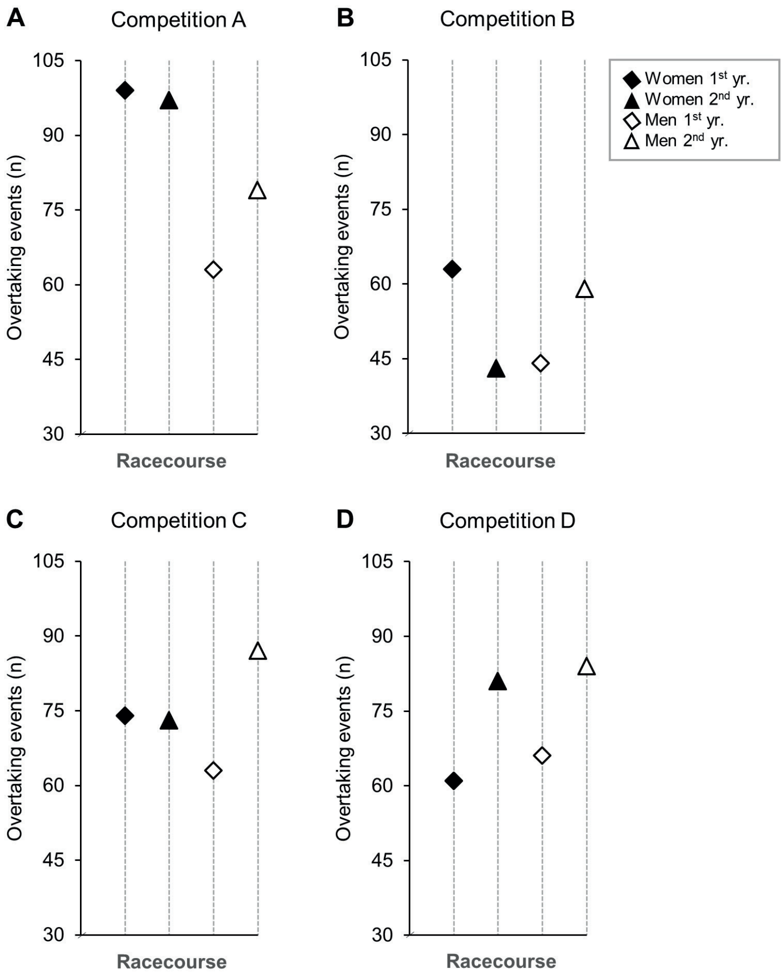

Fig 1. The total number of overtaking events. Overtaking events in two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style) [(N = 30 male and N = 30 female skiers within each of the eight competitions in this study)].

https://doi.org/10.1371/journal.pone.0287717.g001

skiers in the STT, QFs and SFs could potentially choose subsequent heats with longer or shorter recovery times [22].

Consistent with the findings of Haugnes et al. [14], the correlation coefficients between intermediate ranks and final ranks during the heats showed a gradual increase from the first to the last checkpoint, for both sexes and styles. It was observed that 94% of the heat winners in the classical style and 100% of the heat winners in the skating style were ranked among the top-two at the last checkpoint before the finish sprint. However, it is noteworthy that 31–41% of those ranked among the top-two at the finish were outside the top-two when leaving the stadium (i.e., checkpoint 1), while 34–44% of the heat winners were leading when leaving

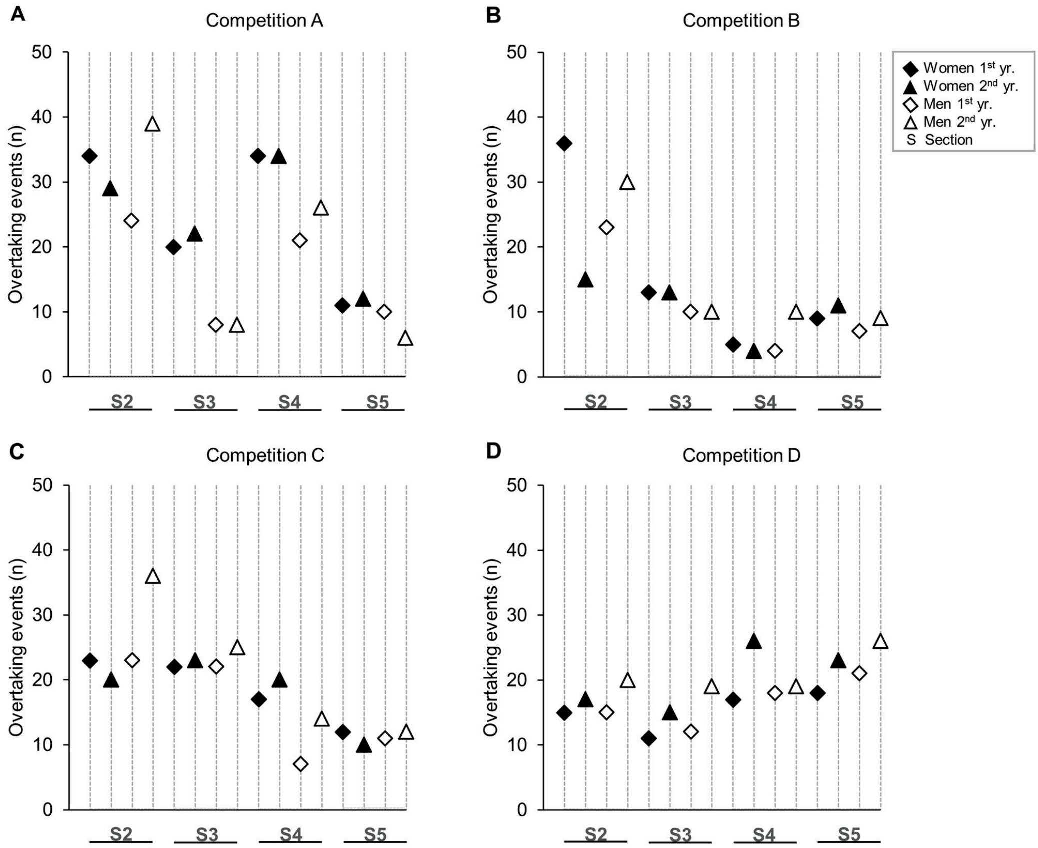

Fig 2. The number of overtaking events in different segments. Overtaking events in two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style) [(N = 30 male and N = 30 female skiers within each of the eight competitions in this study)].

https://doi.org/10.1371/journal.pone.0287717.g002

the stadium. In contrast, Andersson et al. [13], found that most heat winners (61%) of both sexes were in front already after the initial 30 meters of their respective heats, and that 95% of the heat winners were ranked top-two out of the stadium. This difference might be explained by the fact that there was a larger heterogeneity in performance level among the skiers investigated in the study of Andersson et al. [13], and that the present study included some of the world's best XC sprint skiers competing in homogenous heats in world-cup competitions. Extending upon previous findings [14], we found larger correlation coefficients at the last checkpoint in the skating compared to the classical style ($\tau = \sim 0.82$ vs. ~0.70) for both sexes. This could indicate that competitions in the skating style are more often decided at an earlier stage than competitions in the classical style, which might be due to the difficulty to pass other skiers in the skating style where each skier occupies more of the track width. This was further supported by indications of less accidents in the classical compared to skating style (see Table 1). Moreover, the larger correlation coefficients in the skating style could also explain why there were on average fewer overtaking events in the heats

Table 2. The average percentage distribution of intermediate rank of the heat winner at various checkpoints is presented for classical (left) and skating (right) styles during two repeated sprint cross-country skiing competitions held at four different venues (two classical and two skating). Presented as percentages [N = 8 male and N = 8 female skiers within each of the eight competitions in this study].

Variable	Heat winner classical						Heat winner skating					
Checkpoints 1–5 Women	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6
1. Out of stadium	44%	19%	12%	0%	12%	13%	38%	31%	6%	19%	6%	0%
2. End of first part	44%	29%	16%	0%	4%	7%	31%	44%	25%	0%	0%	0%
3. End of middle part	50%	28%	16%	0%	6%	0%	50%	31%	13%	6%	0%	0%
4. Before the finish sprint	69%	25%	6%	0%	0%	0%	75%	25%	0%	0%	0%	0%
5. Finish	100%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
Checkpoints 1–5 Men	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6
1. Out of stadium	34%	25%	16%	6%	19%	0%	39%	20%	20%	7%	7%	7%
2. End of first part	29%	39%	14%	11%	7%	0%	44%	31%	0%	6%	19%	0%
3. End of middle part	44%	34%	6%	9%	7%	0%	50%	44%	6%	0%	0%	0%
4. Before the finish sprint	53%	41%	3%	0%	3%	0%	63%	37%	0%	0%	0%	0%
5. Finish	100%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%

Checkpoint 5 Finish: All heat winners were ranked 1.

https://doi.org/10.1371/journal.pone.0287717.t002

during skating compared to classical competitions (~16 vs. ~20). In the skating style, the highest-ranked skiers more often positioned themselves in the front of the heats at an earlier stage (see Fig 3 and Table 2), and thus controlled the speed in the heat and likely also avoided accidents. Therefore, these findings demonstrate that race tactics might be particularly important in the skating style due to the more limited opportunities to overtake other skiers compared to the classical style.

No significant difference in number of overtaking events between the seasons investigated for both sexes and styles were found, indicating that the number of overtaking events on the same racecourse are relatively consistent. Still, we found a significant sex-difference in the number of overtaking events in one out of the 16 competitions, where women performed more overtaking events than men throughout the racecourse both seasons. This sex-difference was particularly explained by more overtaking events in the middle part of the racecourse. Skiing speed was not examined in this study, but it would have been interesting to know whether speed differences between sexes could explain why women performed more overtaking events in these terrain segments. Furthermore, the competitions analysed had relatively similar conditions, despite some variations (see Table 1). However, differences in external conditions could have influenced the skiers tactical positioning and overtaking events for both sexes, however, this remains to be investigated. Future studies should examine the effectiveness and metabolic cost of the skiers' race tactics. Altogether, these findings demonstrate that a similar number of overtaking events can be expected in competitions held on the same racecourse under comparable external conditions.

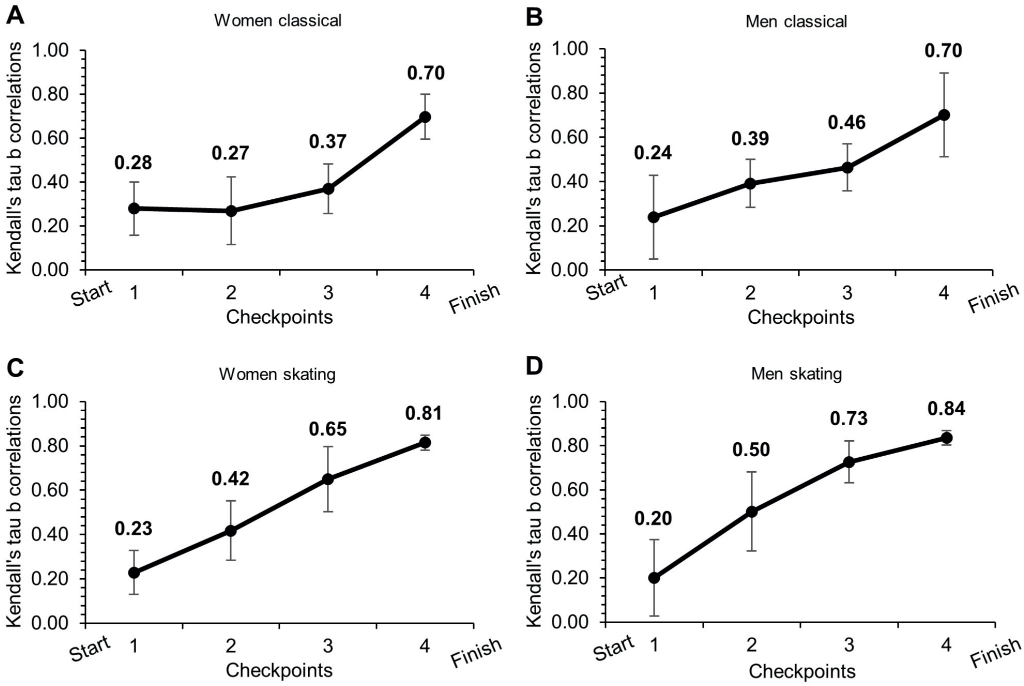

Fig 3. Kendall's tau-b correlations. The relationship between intermediate ranks at given checkpoints and final rank in two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style) [N = 30 male and N = 30 female skiers within each of the eight competitions in this study].

https://doi.org/10.1371/journal.pone.0287717.g003

Conclusions

This study describes the role of tactical positioning in sprint XC skiing. Throughout the heats, there was a gradual increase in the relative importance of being positioned at the front, in which the majority of performance-variance was decided before the start of the finish sprint both among men and women in the classical and skating styles. Notably, the final rank for both sexes was decided at an earlier stage in the skating style compared to the classical style, which is likely explained by greater possibilities for tactical positioning during the heats in the classical style. The number of overtaking events were relatively consistent across seasons, so a similar number of overtaking events can be expected when a competition is repeated on the same racecourse under comparable external conditions. The practical relevance of this study is the novel illustration of how tactical positioning influence performance in sprint XC skiing, and that the number of overtaking events is relatively consistent for competitions performed on the same racecourse.

Supporting information

S1 Appendix. The difference in overtaking events between sexes in the same racecourse over time in two repeated sprint cross-country skiing competitions at four different venues (two classical and two skating style) [(N = 30 male and N = 30 female skiers within each of

the eight competitions in this study)].
(PDF)

S1 File. Data and analyses conduced in this study.
(XLSX)

Acknowledgments

The authors would like to thank FIS for their willingness to share competition data.

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ISBN 978-82-326-7170-0 (printed ver.)
ISBN 978-82-326-7169-4 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

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