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Thesis for the Degree of Philosophiae Doctor

Doctoral thesis

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List of publications

This thesis is based on the four studies listed below which are referred to by their Roman numerals throughout the text.

I. Luchsinger H, Kocbach J, Ettema G, Sandbakk Ø (2018) *Comparison of Performance-Levels and Sex on Sprint Race Performance in the Biathlon World Cup*, International Journal of Sports Physiology and Performance, 13:360-366, https://doi.org/10.1123/ijspp.2017-0112

II. Luchsinger H, Kocbach J, Ettema G, Sandbakk Ø (2019) *The contribution from cross-country skiing and shooting variables on performance level and sex differences in biathlon World Cup individual races*. International Journal of Sports Physiology and Performance, 14:190-195, https://doi.org/10.1123/ijspp.2018-0134

III. Luchsinger H, Kocbach J, Ettema G, Sandbakk Ø (2020) *Contribution from cross-country skiing, start time and shooting components to the overall and isolated biathlon pursuit race performance*, PloS One, 15:9, https://doi.org/10.1371/journal.pone.0239057

IV. Luchsinger H, Talsnes RK, Kocbach J, Sandbakk Ø (2019) *Analysis of a Biathlon Sprint Competition and Associated Laboratory Determinants of Performance*, Frontiers in Sports and Active Living, 1:60, https://doi.org/10.3389/fspor.2019.00060

Summary

Biathlon is an Olympic winter sport combining cross-country (XC) skiing in the skating technique with rifle marksmanship. Biathletes ski loops of 1.5-4 km with shooting between laps in either the prone or standing position. The cross-country (XC) skiing part of the competition is performed on XC-skiing tracks on undulating terrain differing between uphill, downhill and flat or varied terrain. The shooting takes place directly between each lap of skiing on a 50 m outdoor shooting range where the circular targets have hit areas of 45 mm in prone position and 115 mm in standing. Biathletes use 0.22 caliber rifles that the athletes carry on their back while skiing. In single-start races each shooting comprises of 5-shot-series in the prone or standing shooting. For each missed target at the shooting range, biathletes are either penalized with extra time (i.e. 60 s in the individual 15/20 km event) or a 150 m extra loop of skiing (~22s). Seven championship biathlon events exist with varying skiing distances for each shooting and penalty for missed targets across events. The overall purpose of this thesis was to study the contribution of the different race components in biathlon sprint, individual and pursuit races in both genders as well as the association between sprint race performance and laboratory measured capacities.

In study I, the aim was to analyze to what degree the different race factors contributed to the overall performance in World Cup sprint races. The results revealed that course time was the most influential factor for overall performance in both sexes in sprint races explaining approximately 60% of the performance level difference. This was followed by shooting performance explaining more than 30% between a top-10 result and a result among 21st and 30th place. Shooting time and range time only contributed little or nothing to the overall performance in sprint races. In study II, we hypothesized that shooting performance would explain a larger part of the overall differences between performance groups in individual World Cup biathlon races than in sprint races due to the increased penalty time for each missed shot. Indeed, course time and penalty time contributed similarly to the performance-level differences whereas course time explained above 90% of the sex differences. In study III, the aim was to analyze the contribution of the different race components in pursuit World Cup competitions. The results show that 84% and 81% of all victories were achieved by athletes starting as number 5 or better among men and women. In most of the races investigated in men and women, 50% of the overall performance among top 30 athletes was explained by start time. In these races, penalty time was ranked as the second most important component. In a few other races, penalty time was ranked as the most important contributing component explaining on average 40% of the overall performance in these races. Penalty time was also the most contributing factor for

the isolated pursuit race explaining 55-60% followed by course time explaining approximately 30% of the isolated pursuit race time. Standing shooting explained most of the variance in penalty time, but no difference in impact between the third and fourth shooting was found. Together these findings also highlight the importance of the shooting component and especially performance in the standing shooting to overall and isolated pursuit race performance.

In study IV the aims were to investigate the contribution from overall XC-skiing performance, the performance in different terrain sections and shooting performance to the overall performance in a biathlon sprint race. The relationship between these variables and laboratory-measured capacities obtained during treadmill roller ski skating were also investigated. The results showed that the XC-skiing performance provided greatest impact on biathlon sprint performance, with most of the variance determined by XC-skiing performance in the uphill terrain sections. Furthermore, low rates of perceived exertion (RPE) and low relative heart rates (%HRmax) during submaximal constant speeds, as well as time-to-exhaustion (TTE) during incremental roller skiing significantly predicted biathlon performance. Such laboratory-derived measures could therefore be used to distinguish biathletes of different performance levels and to track progress of their XC-skiing capacity.

The overall conclusions are that course time is the most important race component for the overall performance in biathlon sprint races, that course time and penalty time are more similarly important in individual races than in sprint races and that start time explain most of the performance in pursuit races. Biathletes at World Cup level miss more targets in standing than in prone shooting but there is no sex difference in shooting performance (number of misses) except that women use more time for shooting than men. In addition, better performing athletes pace their races more evenly and gain most time in uphill sections of the race compared to lower performing athletes. Better course times in a sprint race was correlated to lower RPE, %HRmax as well as TTE from submaximal tests and a maximal test.

Sammendrag

Skiskyting er en Olympisk vinteridrett som kombinerer langrenn og skyting. Skiskytterne går 1.5-4 km-runder med skyting, enten i liggende eller stående posisjon, mellom rundene. Langrennsdelen av konkurransene gjennomføres i fri teknikk (skøyting) i kuperte langrennsløyper med motbakker, nedoverbakker og variert terreng. Skytingen gjennomføres fra en standplass 50 m fra fem sirkulære blinker med treffområde på 45 mm i liggende og 115 mm i stående. Skiskytterne bruker 0.22 kaliber salongrifler som de må bære med seg på ryggen under langrennet. I alle renn med individuell start skytes det fem skudd av gangen, enten liggende eller stående mellom hver av rundene. For hver bom må skiskytterne enten gå en strafferunde på 150 m eller får tilleggstid (f.eks. 60 s på normaldistansen). Det arrangeres 7 forskjellige rennformat i mesterskap med varierende distanse på langrennet og antall skytinger. Hovedformålet med denne avhandlingen var å studere bidraget fra de forskjellige delene av en skiskytterkonkurranse på sprint, normal og jaktstart for totalprestasjon hos begge kjønn, i tillegg til å undersøke sammenhengene mellom detaljerte analyser av et sprintrenn og laboratorie-målte variabler fra laboratorie-testing på rulleski.

I studie I var hovedformålet å analysere bidraget fra de forskjellige delene av en skiskytterkonkurranse til overordnet prestasjon i sprintrenn i verdenscupen. Resultatene viste at langrennstid var den viktigste faktoren for totalprestasjonen blant både kvinner og menn og forklarte omtrent 60% av totalprestasjonen, etterfulgt av skyteprestasjon (straffetid som følge av bom) som forklarte mer enn 30% av forskjellen mellom et topp-10-resultat og en plassering mellom 21 og 30. plass. Skytetid og standplass-tid forklarte lite eller ingenting av totalprestasjonen i sprintrenn.

I studie II var hypotesen at skyteprestasjon ville forklare mer av totalprestasjonen i normaldistansrenn enn i sprintrenn på grunn av den økte relative størrelsen på straff som følge av bom i forhold til langrennstid. Den hypotesen ble bekreftet av analysene som viste at langrenn og skyteprestasjon bidro omtrent likt til forskjellene i prestasjon. I tillegg var mer enn 90% av forskjellen mellom kjønn forklart av langrennstid (menn 12% raskere i sporet enn kvinner) når langrennstiden var normalisert for distanse (kvinner 15 km og menn 20 km).

I studie III var formålet å analysere bidraget fra de forskjellige delene av en jaktstartkonkurranse. Resultatene viste at 84 og 81 % av alle seire er vunnet av utøvere som starter som nummer fem eller bedre blant menn og kvinner. I de fleste renn blant menn og kvinner forklarte starttid (resultatet på foregående sprintrenn) 50% av prestasjonen blant topp 30-utøvere. I disse rennene var skyteprestasjon rangert som nest viktigste faktor for

totalprestasjonen og forklarte omtrent 30 % av variasjonen i totalprestasjonen utover de 50% forklart av starttid. Skyteprestasjon var den viktigste faktoren for den isolerte jaktstarttiden (når start-tid er ekskludert fra analysene) og forklarte 55-60% av variansen, etterfulgt av langrennstid som forklarte ytterligere 30% av den isolerte jaktstarttiden. Stående skyting forklarte mesteparten av variasjonen i strafferundetid, men det var ingen signifikant forskjell i bidrag til totalprestasjon fra tredje eller fjerde skyting. Skytetid bidro lite til totalprestasjon, men forklarte 8-9 % av den isolerte jaktstarttiden og er dermed viktig for å klatre plasser i jaktstartkonkurransen. Analysene viser viktigheten av skyteprestasjon og stående skyting spesielt for den totale og isolerte prestasjonen på jaktstart.

I studie IV var formålet å undersøke bidraget fra total langrennstid, tid i ulike deler av langrenn i forskjellige terrengtyper, samt skyteprestasjon i tillegg til skytetid og standplasstid for totalprestasjonen i et sprintrenn. I tillegg ble disse faktorene korrelert mot laboratorie-målte variabler fra rulleskitester på tredemølle. Resultatene viste at langrennstiden var den viktigste faktoren for totaltid i sprintrennet, hvor størsteparten av langrennstiden var forklart av motbakketid. I tillegg var lavere opplevd anstrengelse og prosent av makspuls under rulleskiintervaller på konstant hastighet i forskjellige delteknikker i tillegg til tid til utmattelse i en maksimal-test med gradvis økende belastning korrelert med totalprestasjon i sprintrennet. Disse relativt enkle laboratoriemålingene kan derfor brukes for å skille utøvere på forskjellige nivå og til å dokumentere utvikling av utøvernes langrennskapasitet.

De overordnete konklusjonene er at langrennstid forklarer mesteparten av totaltiden i sprintrenn, mens langrennstid og skyteprestasjon er mer likestilt som forklaringsvariabler på normaldistansen og at starttid forklarer mesteparten av prestasjonen i jaktstartkonkurranser. Skiskyttere på toppnivå i verdenscupen bommer mer på stående enn på liggendeskyting, men det er generelt ingen kjønnsforskjell i skyteprestasjon (antall treff) bortsett fra at kvinner bruker lengre tid, både til førsteskudd og på hele skyte-serien. I tillegg går utøvere som presterer bedre med likere rundetider enn utøvere som presterer dårligere og spesielt beholder de som presterer best, nok energi til å gå sisterunde fortere enn nest-siste runde.

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Introduction

Motivation for this thesis

Biathlon is an Olympic winter sport combining cross-country (XC) skiing in the skating technique with rifle marksmanship. Biathletes ski loops of 1.5-4 km with shooting between laps in either the prone or standing position. The cross-country skiing part of the competition (course time) is performed on XC-skiing tracks on undulating terrain, differing between uphill, downhill, and flat or varied terrain. The shooting takes place directly between each lap of skiing on a 50 m outdoor shooting range where the circular targets have hit areas of 45 mm in prone position and 115 mm in standing. Biathletes use 0.22 caliber long rifles that the athletes carry on their back while skiing. In single-start races, each shooting comprises of 5-shot-series in the prone or standing shooting. For each missed target at the shooting range, biathletes are either penalized with extra time (i.e. 60 s in the individual 15/20 km event) or a 150 m extra loop of skiing. Previous studies have revealed stronger associations between course time and overall performance than for shooting performance,[1-3] and correlation to overall performance indicated a stronger association between course time and performance in sprint races than for individual races.[4] These studies were performed 16-28 years ago and updated and detailed analyses of each race factor's contribution and their interplay to the overall performance in several biathlon World Cup competitions provide an updated and better understanding of biathlon, including knowledge of high interest to coaches and athletes that can help to prioritize different aspects of performance in their training.

Seven official championship biathlon events exist and the original individual distance was included as an official event in the first biathlon World Championships in Austria in 1958, followed by the relay (1960), sprint (1974), pursuit (1997), mass start (1998), mixed relay (2005) and the single mixed relay (2015). Women could compete for the first time in the World Championships in Chamonix in 1984 and in the 1992 Olympic Winter Games in Albertville. Today the sprint competition (7.5 km for women and 10 km for men) includes two shootings between the three laps of skiing, where each missed target requires biathletes to ski an extra 150 m as a penalty. In the individual distance (15 km for women and 20 km for men), athletes compete over five laps of skiing with shooting between each lap (i.e., 4 shootings) and each missed target is penalized with 60 s added time. In pursuit races, the 60 best athletes from the sprint race chase the leader over 12.5 and 10.0 km for men and women, respectively. The start time in the pursuit race is identical to the result of the sprint race performed 1-2 days before. The pursuit includes two prone and two standing shootings where the penalty loop is the same as for sprint races (150 m for both men and women). An overview of the design of all the different events for men and women in biathlon can be found online at the official website for the International biathlon Union (IBU): biathlonworld.com/downloads (http://res.cloudinary.com/deltatre-spa-ibu/image/upload/nk93tbz7syaoj02qmjod.pdf).

The individual distance is considered the original event and was until 1974 the only competition that was not a relay. Today, the sprint distance is the most common distance in the World Cup season and very often it is followed by a pursuit race the next or the second next day. Therefore, the sprint distance is the most important competition in the World Cup calendar not only because it is the most common event itself, but it sets the foundation for the result in the pursuit race. Together, the sprint and the pursuit races comprise 17-19 of the 26 single-start events in a normal World Cup year. It is therefore also interesting to analyze which race factors contribute the most to both the isolated and overall performance in pursuit races. Altogether, analyses of the contribution of the different race components in individual, sprint and pursuit races could provide important information to coaches and athletes because they can prioritize their training according to these findings and to IBU when eventually designing new race formats. In addition, because of the preparation phase before shooting and since the HR responses in a biathlon competition has not been investigated in 30 years, a detailed analysis of a biathlon sprint competition using GPS and HR-monitors can provide essential knowledge about performance demands in biathlon. Connecting these analyses from an actual competition to laboratory tests could help coaches and support personnel in guiding athletes to develop as biathletes.

History of competitive biathlon

Originally, biathlon was formed as a sport rising from modern pentathlon. Modern pentathlon was introduced by the founder of modern Olympic Games, Pierre de Coubertin, as a combination of five sports that were considered important for a modern soldier (fencing, swimming, jumping, and a combination of shooting and running). At first, biathlon was governed by Union Internationale de Pentathlon Moderne (UIPM, and later UIPMB as biathlon was added) and biathlon was part of the Olympic Winter Games for the first time in the 1960 Olympic Winter Games in Squaw Valley. Shortly after these games, the International Olympic Committee (IOC) wanted to take biathlon out of the official Olympic program due to its association to the military.[5] Partly because of that and for safety reasons the official rifles used in biathlon changed from caliber 6.5 x 55 mm rifles and 150/200 m shooting ranges to small bore rifles of 5.6 mm x 45 mm caliber (more commonly referred to as 0.22 caliber) and 50 m ranges in 1978. The use of small-bore rifles and metal targets that directly displayed the shooting result markedly had its impact on the popularity of the sport. Although some early attempts with balloons and glass to display hit or miss with large-bore rifles had been tried before, the metal targets and small-bore rifles revolutionized the spectator experience.[5] In 1998, IBU separated from the UIPMB and was accepted as an individual federation by the IOC.[6] Following the introduction of the new disciplines' pursuit and mass start in 1997 and 1998, respectively, biathlon became an increasingly popular sport to watch live and on Television (TV). Pursuit races are easy to follow, also for those with minor understanding of the underlying mechanisms of performance in biathlon. There are 60 athletes starting with the same time in-between as in the results of the previous sprint race and the first athlete to the finish line wins the race. This innovation and the success of implementing i.e. pursuit competitions makes it interesting to understand the contribution from the different race factors in pursuit races compared to the single-start competitions.

In their attempt to analyze why biathlon had become such a popular sport among spectators in relatively short time, Solberg et al.[7] found that the innovation could take place because of a strong international federation owning TV-rights and governing organizers of biathlon events. It would be much more difficult if the host organizers decided which types of competitions and race formats that suited their needs better, the authors concluded. In the process of trying to make the sport more interesting to spectators, the pursuit race was born. The disciplines that are easiest to follow for inexperienced viewers are the races where the first athlete or team crossing the finish line wins the race, and for that reason the pursuit race became one of the most popular to watch. It is still unknown however, how the different race factors course, range, shooting, and penalty time contribute to the overall performance in different types of events and IBU has no such data publicly available.

Course time in biathlon

Course time is the time spent skiing excluding the time at the shooting range. Biathletes carry a ~4-kg rifle while XC-skiing in the skating technique on undulating terrain consisting of uphills, downhill and flat sections and many turns along the course. In absolute time, course time is the largest component of a biathlon competition and requires biathletes to master a complex whole-body movement on snow with high speeds using poles that are controlled by the arms, and a thin pair of skis attached to special shoes. The XC-skiing part of modern biathlon, where the skating technique is used, consists of different gears that the athlete can switch between depending on the terrain to optimize the effectiveness or maximize the power and speed of the propulsion using both the arms (with poles) and legs. The different gears are more extensively described in Andersson et al. (2010),[8] and the biggest difference between XC-skiing and skiing in biathlon is the rifle that the athletes must carry along the track. In contrast to biathlon where less than 100 published peer-reviewed articles exist,[9] XC-skiing has been studied quite extensively.[10-19] Thus, relevant studies on XC-skiing are therefore included in this review.

Twenty years ago, correlation analyses from the World-Cup indicated that course time was more important for overall performance in biathlon sprint races than in individual races,[4] and the contribution from the different race components to the overall performance in the Olympic relay in 1992 was analyzed.[3] However, the speed in biathlon competitions has increased during the last decade,[9] which could have an impact on the contribution of the different race components since higher speed with constant length for each event type (i.e. 10 km and 7.5 km in sprint races for men and women, respectively) necessarily creates shorter course times. This aspect requires a reappraisal of analyses on the importance of the different race components in biathlon events. Another aspect of interest is the impact of the different terrain sections for course time and overall performance in biathlon. While this has not yet been studied in biathlon, uphill performance explains most of the variance in overall time in XC-skiing competitions.[14,20]

When competitions are held over several laps (i.e. a 15 km is performed over 5 x 3 km laps or 3 x 5 km laps), several studies have found that an even pacing strategy (i.e. quite equal lap times) is preferable for better performances.[14,21] However, pacing in XC-skiing and biathlon also includes changing effort according to the varying terrain. For example, Haugnes et al. found that the ability to produce maximal work rates were highest in uphill terrain, where also competition work rate and metabolic intensity is found to be highest. However, the percentage of maximal work rate utilized when skiing on lower intensities was highest on flat terrain.[17] This means that an athlete can work closer to their maximal speed in flat terrain when skiing on a given intensity (in terms of HR) than the corresponding speed in uphill terrain. Such aspects of biathlon are currently non-existing.

Since the duration of a biathlon event typically exceeds 20 minutes (sprint races) and sometimes 40 minutes (individual races), most of the performance rely on aerobic metabolism to create energy. When studying the physiology and performances of elite XC-skiers in the laboratory, it has been shown that better athletes have higher maximal aerobic capacity and better gross-efficiency than athletes on lower levels, and upper-body power seem to be the most determining factor explaining sex differences in XC-skiing performance.[15,22] When testing a group of biathletes in the laboratory however, Rundell and Bacharach found that peak oxygen uptake (VO_{2peak}) in an all-out test did not correlate with biathlon performance whereas treadmill run-time to exhaustion was associated with better course times in a 20 km biathlon race.[23] In line with the findings from XC-skiing absolute and relative power in a 10 s upper body poling test correlated with national ranks and shorter skiing times for women.[23] Since biathlon has evolved significantly since these studies were performed and technological measurement tools and software create possibilities of detailed analyses of a biathlon race it is relevant to perform such analyses on elite biathletes today.

Previous studies on rifle carriage also show that the rifle affects the skiing technique, both in terms of extra physiological cost due to the extra weight itself i.e. in uphill sections but also as technical alterations.[24] In addition, biathletes slow down to prepare for the shooting and thus the pacing strategies in biathlon could be different than in XC-skiing.[3] Therefore, it is relevant to analyze the association between laboratory measurements when skiing both with and without the rifle, and also investigate how biathletes pace the race differently.

Rifle marksmanship and shooting in biathlon

Shooting in biathlon comprise of both prone and standing shooting. In prone shooting the athlete lies down on the stomach, fixing the rifle between the shoulder, cheek and both arms that are placed along the wooden shaft with both elbows placed on the ground. In standing position athletes typically place their feet parallel to the shooting direction and some athletes place the foot that is farthest away from the targets a little forward across shooting direction for better stabilization. The elbow closest to the targets is placed on the hip and the hip is tilted upwards for support, moving the center of pressure in shooting direction. The right hand pulls the rifle towards the right shoulder to fixate the rifle as much as possible. When the heart beats rapidly after skiing, it is the biathlete’s ultimate challenge to both fixate the shooting position and at the same time relax to avoid muscle tremor, that obviously affect shooting performance.[25]

In biathlon, the shooting is performed on a 50-m shooting range between laps of skiing, both from prone and standing position. Several studies have analyzed performance variables of rifle shooting, mostly in standing position, and a few studies have investigated biathlon shooting performance after exercise.[26,27]

The intensity while skiing in competition has previously (in 1992) been found to be approximately 90% of HRmax.[28] The researchers also found that the HR dropped to approximately 85-87% prior to shooting, whereas during shooting, the HR dropped to approximately 60-70% HRmax and 20 beats per minute lower in prone than standing, but these findings were valid for biathlon competitions in the beginning of the 90's and it is unclear if these HR intensities in different parts of the competition are still relevant for biathlon competitions today.[28] Hoffman et al. found that standing shooting performance was negatively associated with increasing intensity in a cycling-exercise prior to shooting whereas prone shooting was not affected by exercise intensity to the same degree.[29] Previous analyses of biathlete's brain activity using electroencephalography during shooting demonstrated higher frontal theta activity (4-7 Hz in frontal electrodes) indicating a narrow focused attention while shooting.[30] Similar studies from rifle shooting have linked higher amounts of specific frequencies of scalp potential (i.e. in the area around sensorimotor cortex) to increased shooting performance,[31,32] and thus indicate that shooting is a sensorimotor task demanding athletes to selectively act on sensory stimuli that enhances performance. Biathletes need to perform this task of combining the visual feedback from the sight and target, the proprioceptive feedback from the body and pulling the trigger with the index finger at the exact correct moment, and all this must be done with high precision directly after high intensity exercise. Fatigue has previously been linked to lower values of these specific scalp potential frequencies that are linked to better performance,[33] and thus indicate that the exercise might impair this ability to focus on correct sensory stimuli.

In biathlon standing shooting, several studies indicate that "body sway" measured as the movement of center of pressure is negatively associated with shooting performance,[34-36] and this has also been found in rifle marksmanship.[37] More detailed analyses of standing air-rifle shooting however, show that body sway only explain about 1% of the performance variance in experienced shooters, but it indirectly influences the important technical determinants of shooting performance.[38] Ihalainen et al. showed that stability of hold, cleanness of triggering, aiming accuracy and timing of triggering were the most important technical factors affecting air-rifle shooting performance.[38] In this study, stability of hold was defined as the standard deviation in movement of the aiming point in horizontal and vertical directions during the last second before triggering and body sway may indirectly affect this stability. Cleanness of triggering was defined as the movement of the aiming point during the last 0.2 s and aiming accuracy is the movement of the aiming point in the last second before triggering. Timing of triggering was defined as the time interval that the aim point was closest to the center of the target in intervals of 0.2 s before and after the trigger pull. In air rifle shooting the ultimate task is to hit the center of the target. In biathlon, it is enough to hit within the circular hit area of 115 mm in standing and 45 mm in prone and thus the shooting technique differs from air rifle shooting especially in terms of holding the aim point steady before trigger pull. Nevertheless, the same technical factors as in rifle shooting are also relevant for biathlon. Indeed, when analyzing these factors in biathlon standing shooting the same researchers found cleanness of triggering and vertical stability of hold to be the most important factors for performance.[27] In addition, postural balance in shooting direction was related to these technical factors. These factors were also negatively affected by exercise intensity prior to shooting, but both before and after exercise a more experienced group of biathletes scored better and performed better than novice.[27] This is in line with findings from Sattlecker et al. who found the same variables (i.e. movement during the last 0.5 s, stability of hold in vertical direction and movement of center of pressure) to be related to standing shooting performance in an actual competition setting.[26] To be able to maintain a high level of cleanness of triggering and vertical stability of hold when exercise increases seems to be a key for biathlon shooting performance. Altogether, the underlying factors for biathlon shooting, especially in the standing position, is thoroughly analyzed. It is still unknown, however, how biathletes of different performance levels vary in shooting performance, shooting time and range time and how much these factors contribute to overall performance in biathlon World Cup competitions.

Shooting and range times in biathlon

It is not sufficient to simply hit the targets in biathlon, but as the competition time is running also when the athlete enters the shooting range, a biathlete must be efficient both when skiing at the range and also during shooting in order to achieve an excellent overall performance. Groslambert et al. analyzed the contribution of the different phases of a biathlon event to the overall performance in the Olympic relay event of the 1992 Olympic Winter Games.[3] the authors proposed that biathletes could save time by not slowing down before prone shooting and in the installation phase of prone shooting (i.e. time to first shot). It was common then, to slow down markedly before the shooting to lower the heart rate (HR) and prepare for the shooting. The shooting times in that competition were 45-47 s both in prone and standing and those from Hoffman in 1992 were approximately 51-57 s in prone and 45-48 s in standing with times to first shot being approximately 21-30 s in both studies.[28] Groslambert et al. concluded that the time to first shot in standing should be adapted individually to each biathletes capabilities. However, these conclusions were based on data from one single competition a long time ago and how much these factors on average contribute over many races in biathlon competitions today is still unknown. Therefore, the aim of this thesis is to analyze the contribution from the different race components for overall performance in various event types.

Purposes

The overall purpose of this thesis was to investigate the contribution of the different race components on biathlon performance in biathlon sprint, individual and pursuit races in both genders as well as the association between sprint race performance and laboratory measured capacities.

Study **I** aimed to analyze the contribution from XC-skiing time, shooting performance, shooting time and range time to the overall performance in World Cup sprint races, in both men and women.

Study **II** aimed to analyze the contribution from XC-skiing time, shooting performance, shooting time and range time to the overall performance in World Cup individual races, in both men and women.

Study **III** aimed to investigate the importance of course, penalty, shooting, range and start time to the overall and the isolated pursuit race performance in both men and women.

Study **IV** aimed to investigate the contribution from overall XC-skiing performance, the performance in different terrain sections and shooting performance to the overall biathlon sprint race performance, as well as the relationship to laboratory-measured capacities obtained during treadmill roller ski skating.

Methods

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

Study I-III were based on publicly available race reports and results from the International Biathlon Union (IBU) datacenter (2016), with permission to use the data for scientific purposes from IBU. Study IV was based on the detailed GPS analyses of 11 elite male biathlete's performances in an IBU regulated sprint races and performance-determining factors analyzed in the laboratory. An overview of the participants in each study is provided in table 1.

Participants

Table 1. Shows the overview of the participants and methods in the four studies of this thesis.

Variable	Sprint Study I	Sprint – GPS Study IV	Individual Study II	Pursuit Study III
Races (n)	47	1	15	37-38
Participants from each race (n)	20	11	20	30
Main statistical tests	Descriptive T-tests between performance groups and sex	Descriptive Correlation Linear regression	Descriptive T.tests between performance groups and sex	Descriptive Correlation Linear regression
Participants	Male and female World-Cup biathletes placed either top 10 or among 21st and 30th place in each race	National and international level junior and senior biathletes in Norway	Male and female World-Cup biathletes placed either top 10 or among 21st and 30th place in each race	Top 30 in each pursuit race

In study **I** and **II** the top 10-results and results within 21st and 30th place in 47 sprint races during the seasons 2011-12 and 2015-16 were included. In study **III**, all results within top 30 in 38 and 37 pursuit races were included to be able to apply regression models to the datasets. The reason why results behind top 30 were not included in any of studies **I-III** was that including top 30 results ensured that the athletes would compete with full effort on all laps to a higher degree than if e.g. top 60 were also included. In study **IV** eleven elite male Norwegian biathletes were included. All participants in study IV signed written informed consent prior to participating and the study protocols were registered and approved by the Norwegian Social Science Data Services.

Overall design

In study **I-III**, which were based on the race reports from the IBU datacenter, the results were divided in sex and two result categories, top 10 (G1-10) and results within ranks 21 to 30 (G21-30). The final times, course times, shooting times and range times of G21-30 were subtracted from the corresponding times for G1-10. The differences in course, penalty, shooting and range time were divided by the difference in overall time between G21-30 and G1-10. In study **III** Stepwise multiple regression analyses were applied to each of the 37 and 38 races in men and women, respectively using start, course, penalty, shooting and range times behind the winner or the fastest athlete in the isolated pursuit race as independent variables and time behind the winner or the fastest athlete in the isolated pursuit race as dependent variable. Each race was analyzed separately, and descriptive statistics were applied to the 37 and 38 model outcomes. In addition, for this thesis an analysis of the average time behind winner in the different race components for each overall rank was performed (not included in the paper).

Example of how the computation of the variables in study III (i.e. the pursuit races) were done is provided in Appendix A.

Experimental study - Study IV

Overall design

In study **IV** the 11 biathletes were tracked by a Global Positioning System (GPS) device and a heart rate (HR) monitor during an international IBU-regulated 10-km biathlon sprint competition. Details of the competition and the course profile are provided in the methods section of study IV. The analyses from this sprint race were correlated with physiological measurements [i.e. oxygen uptake, RPE, $\%HR_{max}$ and time to exhaustion (TTE)] from the laboratory testing.

Test protocols

Within a period of 6 weeks prior to the competition in study IV, physiological responses, and performance during submaximal and maximal treadmill roller skiing were measured. In this test setting the biathletes performed 6x5 min submaximal stages after a standardized warm up session. These submaximal stages were split in three different speeds and inclines that were matched for intensity, such that each athlete performed 2x5 minutes in three different gears, one interval with and one without the rifle on the back. After completing these stages of sub-maximal skiing and a short break, the athletes performed a maximal test to exhaustion in an incremental test where elevation and/or speed increased every minute. This maximal test was carried out without the rifle on the back. Physiological measurements were conducted by a skilled test leader in a regularly validated laboratory. During the competition no interference with the athlete occurred, except ensuring that the wristwatch was correctly started. The athletes chose their preferred warm-up procedure and used their own equipment during the competition. The software used to analyze the GPS and HR data was developed by the Norwegian Olympic Sport Centre and the section time analyses are based on creating a reference course and fitting all other GPS datapoints from other laps from all the participants onto this reference course (See figure 1 for a map of the race course). This can be done by a mix of speed, position and shape of the course.[39] Then virtual split times of 10-15 s are created. With this method, the accuracy of the converted data from the GPS-device is much higher than if the analyses were based on raw data only and this method has been validated against more accurate heavier GPS-devices.[39] In addition, the athlete can ski with a normal wristwatch which does not affect the athlete to the same degree as a more accurate heavier device which assured that athletes on a high level could participate although it was a real biathlon competition since the wearable sensors had no impact on performance.

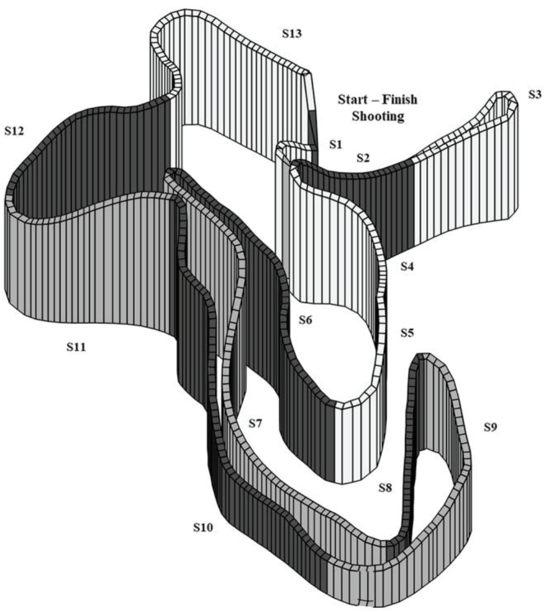

Figure 1. 3D illustration of the 3015 m long racecourse divided into 13 different terrain sections. The dark areas are uphills, grey areas downhills and white parts are “varied” terrain sections. Detailed description of the different terrain sections (S1-S13) can be found in the methods section of paper IV.

Equipment and materials

During the competition, each participant was tracked by a Polar V800 GPS (Polar Electro Oy, Kempele, Finland). Course and elevation profiles of the racecourse were measured with an integrated GPS and barometry using a Garmin Forerunner 920 XT (Garmin Ltd., Olathe, Kansas, USA). Weather conditions were continuously registered during the competition using a weather station (delivered by Airtight Ltd., Oslo, Norway) developed by The Norwegian Top Sport Centre (Olympiatoppen). Treadmill roller skiing was performed on a 5 x 3-m motor-driven treadmill (Forcelink B.V., Culemborg, The Netherlands) with non-slip rubber surface on the treadmill belt, allowing the participants to use their own poles with special carbide tips. Respiratory variables were measured using open-circuit indirect calorimetry with mixing chamber and 30 s averages of the respiratory variables (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany). The flow transducer (Triple V, Erick Jaeger GmbH, Hoechberg, Germany) was calibrated using a 3-L high-precision calibration syringe (Calibration syringe D, SensorMedics, Yorba Linda, CA, USA). HR was continuously measured with a Polar V800 monitor and synchronized with the Oxycon Pro system. The participants' body-mass and mass of the rifle were measured using a precise weight (Seca, model 708, GmbH, Hamburg, Germany)

Statistical analyses

The details of the statistical analyses in each study are found in the methods section of each study included in this thesis. Briefly described, in study I and II, mostly descriptive analyses and t-tests were used to analyze differences between performance groups and sex. In study III and IV descriptive analyses, stepwise regression models and correlation analyses were used. Outliers and extreme values were treated such that assumptions for using the different statistical tests were met. Partly, the analyses included datapoints that were considered outliers statistically to ensure analyses of the whole dataset (i.e. all athletes) as well (details are stated in the methods section in study IV). All statistical tests were performed in SPSS version 24-26 (IBM Inc., Armonk, NY, USA) and Microsoft Excel version 14.0 (Office 2016, Microsoft Corporation, Redmond, WA, USA).

Results

Overall findings

The overall findings of this thesis were that course time was ranked as the most influential component of sprint races contributing on average 59-65% to the overall performance in World Cup competitions (Study I). Penalty time was ranked as the second most important component in all event types except in individual races contributing similarly as course time in these races. The overall findings from the studies in this thesis are found in Table 2.

Table 2. Shows the contribution of each race component to the overall performance across event types in the four studies in this thesis

Race component	Sprint Study I	Sprint – GPS Study IV*	Individual Study II	Pursuit Study III*	Isolated Pursuit Study III*
Course time (%)	59-65	84	42-54	15-16**	30-35
Penalty time (%)	31-35	14	44-53	30**	55-60
Shooting time (%)	2-4	1-2	1-3	4-5	8-9
Range time (%)	0-2	-	0-2	0-1	0-1
Start time (%)	-	-	-	50	-

*In study III and IV stepwise multiple regression analyses were applied. Therefore, the contribution from each race factor in these studies refers to the remaining variation in overall performance explained by this component after the more important contributing components have explained the largest part of the variation (i.e. start time explained 50% of the variation in overall performance in pursuit study III and penalty time explained 30% of the rest of the variation in overall performance) **In most pursuit races. In some pursuit races, and more races among women than among men, course time contributed more than penalty time to the overall performance. See details in the specific chapter for study III below.

In addition to the findings on the contribution from each race component's impact on overall performance in each event type, the detailed analyses of a biathlon sprint race using GPS and HR- monitors showed that time in uphill sections separate better from lesser performing athletes the most and that time to exhaustion in a 4-6 min roller skiing test on a large treadmill was strongly correlated to skiing time on the last lap.

Study I

The results from study I showed that course time explained 59-65%, penalty time 31-35% and shooting and range time less than 6% of the total time (corresponding to 3-5% overall time difference) that G21-30 were behind top-10 finishers. Women skied on average 12% slower than men and had on average longer shooting times but there was no sex difference in shooting performance (i.e. number of hits) except in the last standing shooting in individual races among top 10 where men hit 93% and women 90% of the targets. Both men and women in both performance groups skied the first lap faster than the second and third lap with the second lap being the slowest. However, the better performing athletes paced the race more evenly, skiing both the first lap and the last lap closer to the average speed than the lower performing athletes. The average total hit rates were 92–93% among the G1-10 and 85% among the G21-30 in both sexes. In both performance groups and in both sexes there were more misses in standing than in prone, and more misses in standing (80-82% hits) compared to prone shooting (89-90% hits) among G21-30 than in G1-10 (94-95% hits in prone and 90-91% hits in standing). Overall, study I showed that course time is the most differentiating factor for overall biathlon performance between performance levels and sex in World Cup sprint races with penalty time and especially shooting performance in the standing shooting explaining most of the rest of the total time difference between performance groups.

Study II

Study II showed that G21-30 among men and women were on average 4-6% behind G1-10 in total race time, and course time explained 42 and 54% of that overall difference in men and women, respectively. Penalty time (i.e., the number of hits) explained 53 and 44% of the total time difference, and thus, the remaining 2-3% was explained by differences in shooting time and range time. In both performance groups and in both sexes there were more misses in standing than in prone, but only among men there were more misses in standing among G21-30 [(84-88% hits) compared to prone shooting (91% hits)] than in G1-10 (95% hits in prone and 93% hits in standing). Men G21-30 hit 87.5% of the targets during the first standing shooting compared to significantly lower 83.8 % on the second standing shooting, whereas there was no difference between the two standing shootings in women G21-30. The four first out of the total five laps of skiing were skied consecutively slower for each lap in both performance groups for both sexes and the last lap was skied faster than the fourth for G21-30 in both sexes and faster than the third lap for G1-10. The first lap and the last lap was also skied closer to the average speed among G1-10 than among G21-30 and thus the better performing groups in both sexes paced the race more evenly especially on the first and the last lap. Women G1-10 were on average 15% slower in skiing speed than men G1-10, which accounted for 92% of the overall performance difference between sexes. In total among G1-10, men shot on average 15 seconds faster than women being faster on all shots. Men missed the first shot in both prone shootings twice as often than other shots during prone shooting and the odds ratio of a mistake on the first shot during prone in men G1-10 versus women G1-10 was 2.6 for the first prone shooting and 3.0 for the second prone shooting. Thus, men were almost 3 times more likely than women to miss the first shot during prone shooting in individual races. In addition, men G1-10 missed the last shot in the second standing more than twice as often as women.

Study III

Start time, and thus sprint race performance, explained ~50% of the performance-variance in overall pursuit performance in most races. Together with start time, penalty time explained ~80% of the performance variance in 23 and 22 out of the 38 and 37 pursuit races investigated among men and women, respectively. When adding course time on average ~95-96% of the performance variance was explained.

For isolated pursuit performance, penalty time was the most important component, explaining >54% of the performance-variance in 35 and 27 of the 38 and 37 pursuit races among men and women, respectively. This was followed by course time which together with penalty time explained ~91-92% of the performance variance in both sexes in these races. When adding shooting time, these three components of the race explained 99% of the performance variance in the isolated pursuit race (i.e. important to climb places in the pursuit). The results in study III also showed that in 37 and 32% of the races the winner was also the winner of the sprint race and 84 and 81% of the overall winners started as number 5 or better in men and women, respectively. The overall winner had the fastest isolated pursuit race time in 24 and 35% of the pursuit races and had a median start number of 2 starting on average 11.6 and 13.7 s behind the winner of the sprint race in men and women, respectively. The winner of the sprint however, only had the fastest isolated pursuit race time in one race in both sexes. The fastest isolated pursuit race time was generally achieved by athletes starting further behind after the sprint, merely with a median start number of 19 and 12 in men and women, respectively. In both sexes the fastest isolated pursuit race time gave a final rank within top 5 in 76-86% of the races. The overall times for top 30 athletes in the pursuit distances averaged approximately 33-34 minutes and they missed on average 2.6-2.8 out of the 20 shots in both sexes.

When averaging time behind the overall winner for separate overall ranks in pursuit races (not included in the paper), start time was still the component where the different ranks lost most time to the overall winner, as in the linear regression outcomes (figure 2 & 3). Penalty time was the second most contributing component whereas course time was ranked lower or more similarly as shooting time and range time than in the linear regression models.

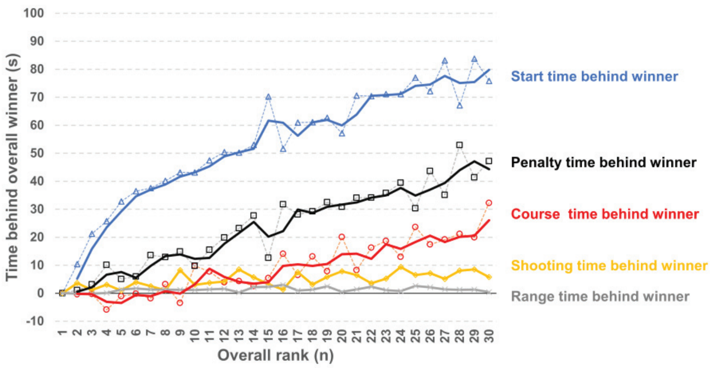

Figure 2. Shows the average time behind winner in the five race components start, penalty, course, shooting and range time for different overall ranks in the 38 races among men. The reference line (thick grey at Y=0 refers to the time of the overall winner in each component of the race).

Among women start time is still the most important component explaining overall rank, when averaging all 37 races. Course time seems to be more important for overall performance than among men as in the linear regression outcomes but contributing more or similarly as penalty time (Figure 2).

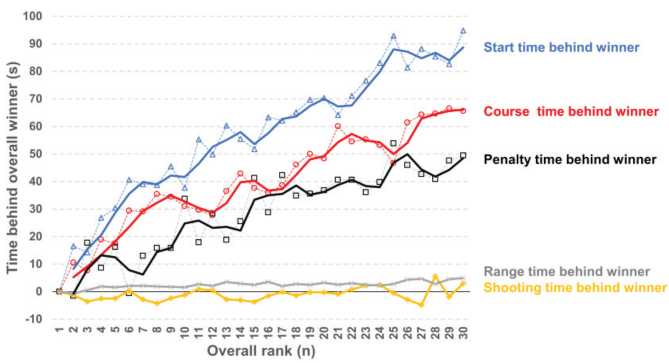

Figure 3. Shows the average time behind winner in the five race components start, penalty, course, shooting and range time for different overall ranks in the 37 races among women. The reference line (thick grey at Y=0 refers to the time of the overall winner in each component of the race).

Study IV

The hit rates of these 11 athletes averaged 91% in prone which was significantly better than the 86% in standing. The average overall time of approximately 26 minutes were in line with the overall times in the biathlon World Cup. Results from the stepwise regression analysis showed that approximately 84% of the sprint race performance was explained by XC-skiing performance, followed by ~14% explained by penalty time and 1-2% by shooting time. Most of the XC-skiing performance (~90% of the variation) was explained by time in uphill sections of the race and the highest coefficients of variation were also found in uphill sections. However, time in all types of terrain correlated with overall competition time and thus the better athletes were generally faster in all types of terrain. The last lap was skied significantly faster than the second lap, but the first lap was skied the fastest, approximately 4 and 3 % faster than the second and the last lap. There were no significant correlations between the time or %HRmax in the section prior to shooting and shooting performance. On average, the athletes' HRs were between 85 and 95%HRmax throughout the race with most of the second and third lap performed with more than 90%HRmax. On average the %HRmax was 87 ± 3% at the start of shooting both in prone and standing position and during shooting %HRmax decreased to 69 ± 6% in prone and 79 ± 4% in the standing position. The shooting times were on average 31 ± 5 s in prone and 27 ± 4 in the standing position. The laboratory measurements from the submaximal stages showed that skiing with the rifle that weighed on average 4.0 ± .3 kg caused a 5% higher oxygen cost, 3% elevated HR and 10-15% (.5 mmol) higher lactate concentrations compared to skiing without the rifle. Correlations revealed that a faster course time was associated to lower RPE and %HRmax during the sub-maximal stages for each sub-technique. In addition, total time to exhaustion (TTE) in the maximal test significantly correlated with overall time and skiing time. When correlated separately, TTE did not correlate significantly with skiing time on the first or the second lap but correlated strongly ($r = -.84$, $p<.01$) with skiing time on the last lap.

Discussion

This thesis analyzed the contribution from course time, penalty, shooting and range time to the overall performance in sprint, individual and pursuit races, as well as the additional impact of start time for the overall pursuit race performance in the biathlon World Cup competitions. In addition, detailed analyses of a biathlon sprint race were correlated to laboratory-measured test capacities in elite male biathletes. The main findings were as follows

1. Course time was ranked as the most influential component of sprint races, explaining on average ~60% of the overall time in World-Cup competitions (Study I), while this was reduced to ~45-55% in individual races (Study II) and 15-16% in most of the pursuit races (Study III).
2. In general, better performing biathletes pace their races more evenly from lap to lap compared to lower performing athletes both in the sprint and individual distance races (Study I & II).
3. In a more detailed analysis of a sprint race where course time explained 84% of the variance in total time uphill sections of the course explained most of the variance in course time (Study IV).
4. Penalty time was ranked as the second most important component in sprint (Study I) and most pursuit races (Study III). In individual races (Study II), penalty time contributed similarly as course time.
5. Of the two shooting positions, prone and standing shooting, standing was the most differentiating for all events, but no difference in the impact from shooting 3 and 4 was found in the pursuit race (Study III).
6. Women used approximately 6% longer time during shooting than men in both sprint (Study I) and individual races (Study II), but no sex difference in shooting performance (i.e. targets hit) were found in top 10 and 21-30 results in both sprint and individual races apart from the last standing shooting among top 10 in individual races were men hit 93% of the targets and women 90%.
7. Men missed the first shot during prone shooting 2-3 times more often than women in individual races and both men and women missed the first shot more often than the second shot in prone in sprint races (Study I). Men top 10 also missed the last shot in the last standing more often than other shots in standing in individual races (Study II).

8. Although standard physiological performance-determining variables such as VO_{2max} and gross efficiency did not significantly correlate to performance in the biathlon event in study IV, RPE and %HRmax on submaximal stages in three different sub-techniques while roller skiing on a treadmill were associated with faster overall time in a biathlon sprint race and longer time to exhaustion in a 4-6 min all out test on the treadmill was correlated with shorter course time on the last lap in this sprint race.

Course time

Course time explained ~60% of the performance difference between top 10 and results within 21st to 30th place in sprint races, approximately 50% in individual races and was ranked as the most influential component for both sexes in sprint races and similar to penalty time in individual races. When analyzing one sprint race only, using multiple regression analysis, course time explained 84% of the overall time. In most of the pursuit races, course time was ranked as the third most contributing factor for overall performance after start time and penalty time. This difference in the importance of course time is explained by the design of the different events. In the individual distance the penalty time for each missed shot is almost three times longer than in sprint races and this is only partly compensated by the longer course distance. Therefore, penalty time is more influential to the overall time in individual races than in sprint races. The apparent difference in contribution of course time to the overall performance in sprint and individual races is in line with previous findings using correlations in the 2004-season,[4] but contribute with updated details of the contribution of each race component. In pursuit races, however, the contribution from course time to overall performance is ranked behind both start time and penalty time in most of the races investigated. With shorter skiing for each shooting in pursuit than sprint races and four compared to two shootings in total, where each mistake results in a penalty loop of equal distance as in the sprint race, the course time in pursuit is shorter than in sprint races. Grouping of athletes and tactics related to the four shootings might contribute to the apparent lower impact of course time in pursuit races than in sprint and individual races. The findings from the pursuit races highlight the importance of performing well in the sprint race in order to succeed in the overall pursuit race, and therefore undermine the importance of course time. However, when analyzing the isolated pursuit race, course time is of more importance than for the overall performance.

Pacing in biathlon competitions

To finish within top 10 on a regular basis in sprint, individual and pursuit races, all the studies in this thesis show that an athlete must hit on average more than 90% of the targets. Therefore, shooting performance in biathlon could be regarded as the "qualifying race factor" to the XC-skiing race for the overall performance, meaning that when one look at the race components selectively an athlete must hit all the targets first, then the best cross-country skier wins the race. In practice, however, the mechanisms are not quite that simple. To hit the targets, the athlete must perform each lap of skiing with an intensity that maximizes each athlete's probability to hit the targets based on this athlete's capacities. Studies I, II and IV showed that on a general basis the best performing athletes ski each lap closer to their average lap time than lower performing athletes and study IV also showed that skiing speed on the last lap (out of the three laps in a sprint) was strongly correlated to time to exhaustion in a 4-6 minutes roller ski skating test on a large treadmill in the laboratory but not to the first or the second lap in the race. This suggest that better performing athletes in an all-out test in the lab adjust their pacing strategy on the first and second lap differently than lower performing athletes and that they have more "reserves" before each shooting. This makes sense considering the fact that both the prone shooting performance[29] and the standing shooting technique[26,27] is highly affected by exercise intensity prior to shooting. In addition, faster course time was correlated to longer relative time in a section prior to standing shooting compared to the time rest of the lap in study IV. However, an association between pacing towards shooting and shooting performance was not found. To investigate how pacing affects shooting performance (hit or miss) it is likely necessary to use a more sensitive measure of shooting performance than hit or miss (i.e. electronic targets to measure spread of the shooting) or include more laps and shootings. It is already known that shooting performance and technique is altered by exercise intensity when comparing rest and activity,[26,27] and that shooting is also altered by ballistocardiac recoil (movements in the rifle as an effect of heart beats)[40] but knowledge about how different pacing strategies in an actual competition affects shooting performance is currently lacking. In study I, we found that top 10 athletes ski the first lap ~2 % faster than their average speed but the third lap faster than the second lap, which indicate that athletes maintain physical resources to the last lap. In study II we found the same pattern in individual races where the first four laps were skied consecutively slower but the last lap faster than the fourth lap, and better performing athletes skied the first and the last laps closer to their average lap times. In XC-skiing it is common with a more positive pacing strategy than seen in biathlon (where J-shaped pacing is more common) which is most likely caused by the shooting in biathlon which creates a motivation to reserve some energy for the last lap. Losnegaard et al. found that XC-skiers utilize 120-160% of the aerobic energy capacity in uphills and use downhill sections to recover. Thus, skiing to fast in the beginning of the race might result in unsuccessful recover. In addition, the same authors concluded that a better overall result in distance races would probably be achieved with a more even lap-to-lap pacing strategy.[21] In a review of existing literature on pacing strategies in cross-country skiing, Stöggl et al. also recommended lower level athletes not to start their races too fast.[41] This seems to be even more important in biathlon, since intensity of exercise affects shooting technique both in prone,[27] and standing shooting.[24,25]

Penalty time

Penalty time was ranked as the second most important component in sprint and in most pursuit races after course time in sprints and start time in pursuits. In sprint races, penalty time explained approximately 31-35% of the overall performance and in pursuit races when 50% of the variance in performance is explained by start time, 30% of the remaining variance in overall performance was explained by penalty time in most races. In individual races, penalty time contributed more similarly as course time, than in sprint races, explaining on average 44-53% of the overall difference in performance between Top 10 and results within 21-30. The difference in the contribution from penalty time to overall performance between sprint and individual races is caused by the 1-minute penalty time for each mistake in individual races compared to the 150 m extra skiing loop (~22s) in sprint races and is not fully compensated by the extra distance of skiing between shootings. In all four studies, the largest amount of penalty time was caused by mistakes in the standing shooting as opposed to penalty time from prone shooting. This is discussed in more detail in study I, but in short, this is likely caused by the more challenging technique with increased degrees of freedom during standing, which causes more movement in the rifle and difficulties in timing of triggering compared to prone shooting. Better biathletes are able to maintain a high pre-shot trigger force even after exercise of vigorous intensity,[26] but several variables related to standing shooting performance were affected negatively by exercise intensity in a simulated biathlon standing shooting task after treadmill roller skiing intervals.[27] These factors included cleanness of triggering and movement of the rifle in the last 0.2 s before trigger pull. Interestingly, in pursuit races shooting 4 (last shooting) did not explain more of the variation in penalty time than shooting 3. It was naturally to expect that the last shooting was more influential than the third shooting as tension builds up towards the end of the race, as found in individual races, especially among men, but this was not the case in pursuit races. Since all studies in this thesis show that standing shootings separate top performances from lower performances, biathletes should probably prioritize standing shooting performance after high intensity exercise more.

Men miss the first shot during prone more often than women in individual races and more often than other prone shots, but in sprint races both men and women miss the first shot almost twice as often as the second shot. From study I and II we know that the first shot is fired approximately after 15-18 s after entering the shooting mat in prone position. In study IV, athletes entered the shooting mat with approximately 86% HRmax with a HR drop to approximately 70% during prone. This HR drop and the instant stop in movement (lying down and shooting) directly after high-intensity exercise may cause changes to the blood pressure that affect the movements in the rifle. In addition, biathletes use their breathing to move the sight during prone shooting and most athletes hold their breath for a short period of time while pulling the trigger. This could affect blood flow and blood pressure, especially since biathletes use a strap around the arm that is connected to the rifle. However, if this change in state from high intensity exercise to rest during shooting affects blood pressure and movement in the rifle differently among men and women is currently unknown. In rifle shooting the timing of triggering related to the cardiac cycle does not influence performance although better performing athletes shot more frequently in a certain time interval of the R-R-signal (i.e. during heart filling).[42] Similar findings exist in biathlon shooting,[40] but it is currently unknown how heart beats affect shooting performance during prone shooting in biathlon competitions.

Range and shooting times

In 1997, Groslambert et al.[3] suggested that biathletes could save some time by not slowing down before shooting and be more effective before the first shot in prone shooting by analyzing the relay event of the Olympic Winter Games in 1992. However, the analyses of biathlon sprint and individual races done in this thesis show that shooting and range time contribute little to the overall performance in these races. This is in line with findings from Skattebo et al.[25] who in 2017 showed that biathletes in sprint races had an equal race-to-race variability in shooting performance and skiing time expressed in seconds of ~18-23 seconds, but only 3.5-4.5 seconds in shooting time. In pursuit races, shooting and range times contribute approximately 3-5% to the overall performance which is similar to the findings in study I and study II. For the isolated pursuit race performance these two race components contributed 6-10% and thus shooting and range times seem to be more important for the isolated pursuit race performance than for the overall pursuit race, sprint and individual race performance. As IBU introduces new events, such as the single-mix relay and super sprint (new event in the biathlon World Cup in 2020) with shorter course times and more impact of the shooting, it has been suggested that fast and clean shooting will contribute more to the overall result in future biathlon competitions.[9] However, the shooting times provided in the studies of the individual start competitions in this thesis can be used as reference for the required level among the best athletes in the world in these event types.

Start time in pursuit races

Study III revealed that in most of the pursuit races, start time was the most contributing race component, explaining on average 50% of the variance in overall performance followed by penalty time and course time. Approximately 80% of the overall victories in world cup events were achieved by athletes starting as number five or better. These findings question the fairness of the competition. The findings in study III shows that athletes starting as number 10 or worse from the sprint race, seldom (only ones out of 37 and 38 races among men/women) win the pursuit race and approximately 90% of top 3 performances (i.e. medals in championships) were achieved by athletes starting better than number 10. This means that only very few athletes (i.e. a generally high ranked athlete in the World-Cup total who underperform in the sprint race) can get to the podium in the overall pursuit competition by starting as number 10 or further behind. Even for rank 2-6 in the overall race, start time is the most important contributing race component to the overall time behind (figure 2 and 3). When there are 8-10 annual pursuit competitions and they are all based on the sprint, the effect of start time for overall performance in pursuit races has an impact on the overall World Cup results. The conclusion highlights the sprint race as the most important factor for overall performance in the pursuit.

Laboratory determinants of course time in biathlon

In study IV, detailed analyses of performance in a biathlon sprint race were correlated to laboratory-measured capacities while skiing on a treadmill. Previous studies from biathlon has shown that TTE during treadmill running and a 1-km double-poling time trial on snow correlated significantly with performance in a biathlon sprint race among men whereas VO_{2peak} did not.[23] Studies from XC-skiing suggest that both the maximal aerobic capacity, upper body strength (especially in women),[43] as well as technical aspects,[44] correlates with performance.

The findings in study IV suggest that aerobic capacity and gross efficiency do not explain the course time differences between faster and slower biathletes in a sprint competition whereas

RPE and %HRmax on submaximal stages both skiing with and without the rifle correlated to overall performance in study IV. This indicate that simply measured variables such as RPE and %HRmax on submaximal steady-state stages of roller skiing can be used to track progress. This is in line with findings from Foster et. al. indicating RPE as a valuable tool for monitoring training.[45] In addition TTE while roller skiing at 14% elevation correlated significantly with course time on the last lap which is in line with previous findings on US biathletes.[23] The fact that TTE correlated with course time on the last lap but not on the previous laps indicate that better performing athletes in the TTE – test save some energy for the last lap during the race.

The detailed analyses of performance in the biathlon race using a GPS-device and a software developed especially for this purpose, showed that time in uphill sections of the race explained most of the variance in course time (although better performing athletes were faster in all types of terrain) which suggest that uphill performance is a key element for biathlon performance, in line with findings from XC-skiing.[14,16]

The uphill sections in study IV, in a course that is accepted by IBU for international competitions, lasted between 22 – 85 s which is shorter than most uphill sections in most races of similar duration in XC-skiing.[14] Findings from XC-skiing suggest that most athletes ski uphill sections well above their maximal aerobic capacity and recover in downhill sections.[17,46-49] Since the uphill sections in biathlon are mostly shorter than those in XC-skiing, the lack of an association between gross-efficiency and VO_{2peak} to overall performance in study IV and the differences to performance determining factors in XC-skiing could result from the differences in course profiles because shorter uphill sections invite athletes to increase the intensity while skiing uphill because of the shorter duration skiing uphill (i.e. next downhill section). Obviously this speculation needs investigation, but evidence from pacing analyses in XC-skiing show that athletes employ work rates as high as 120 to 160% of VO2peak during the uphill sections of the race[50]. With shorter uphill sections in biathlon and the fact that biathletes carry extra 4 kg weight because of the rifle, these work rates could be even higher in biathlon, possibly resulting in a relative greater contribution from maximal anaerobic capacity to performance in biathlon than in XC-skiing. However, it should be noted that championship-medal-winning male biathletes employ higher VO_{2peak}-values (81 ml*kg*min^{-1})[51] than the average of the participants in study IV (~74 ml*kg*min^{-1}). This indicates that increased VO2-peak values is still of benefit for biathletes also, but the fact that biathletes come to a complete stop and must perform accurately during shooting for 20-35 s in between skiing of close to maximal intensity could indicate that O2-kinetics (i.e. forced breaks in between high intensity “intervals”), anaerobic capacities (shorter uphill’s) and race tactics (because exercise intensity might impact shooting performance) play a bigger role for biathlon skiing performance than for cross-country ski races of similar duration.

In addition, the rifle carriage while skiing created higher HR, lactate and rate of perceived exertion (RPE) levels compared to skiing without the rifle among the participants in study IV and previous studies have shown that the skiing technique is altered by rifle carriage.[24,52] However, there were no significant differences in associations between laboratory measured variables and biathlon performance when analyzing the data from testing with or without the rifle on the treadmill which indicate that the biathletes in this study have similarly adopted the skiing technique and skiing performance with the rifle even if the energy cost of the rifle carriage is higher than skiing without.

Methodological considerations

The strengths of study I-III are the number of races investigated and the separate analyses (i.e. correlations and linear regression as well as simple descriptive statistics) that together create robust and valid results that can be generalized to these event types. In addition, this is complemented by the more detailed focus on the sprint distance and its associations to laboratory measured capacities in study IV, allowing us to dig deeper into the contributing factors for overall performance in the sprint race. The analysis tool that was developed by the Norwegian Top Sport Centre (Olympiatoppen) and our research group[14,20,39] made it possible to analyze smaller sections and the different parts of biathlon competitions more thoroughly. These analyses of speed and HR in different sections of the race proved valuable to understand more of the mechanisms of pacing, performance in uphills, downhills and varied sections of the course and their interlink with shooting. Correlating these factors with laboratory measured capacities in a high-end lab specifically designed to test skiers while they exercise with roller skis on a large treadmill altogether created new knowledge about sprint biathlon competitions and the underlying mechanisms of performance. Ideally, the physiological testing should have included a larger number of athletes and been performed closer to the performance date, with the same time interval before the competition. However, including elite level biathletes from different teams to such a study means that some individual adjustments must be done to fit their training program. Although the testing was performed within a period of six weeks prior to the competition and theoretically physiological capacities might develop, it has previously been shown that cross-country skiers employ quite stable physiological capacities in this period prior to season opening.[53]

When generalizing findings from many biathlon events the apparent aspect of each race living its life on each own is sometimes lost. Reasonable unpredictability is one of the key components of popular sports contests and a revolutionary athlete often redefines known performance demands. This thesis prevails performance demands as they appear today, not necessarily in the future. The competition venues differ in terms of altitude, snow conditions and course profile which likely affects the contribution by the different race factors to some degree.[54] This should be taken into consideration when giving advice to coaches and athletes.

Future lines of investigation

There are several articles about standing shooting in biathlon, but not many about the prone shooting. We know that exercise intensity does not influence prone shooting to the same degree as standing[29] and from study I-IV in this thesis that standing shooting in competition separates athletes of different performance level the most. However, prone shooting is still separating athletes of different levels according to findings in study I and II and has not been studied to the same degree as standing. In addition, biathletes' heart beat most certainly affect the movement of the rifle both in prone and standing shooting. In rifle shooting, more experienced shooters pull the trigger to a greater extent in diastole than less experienced marksmen but this timing of triggering has no impact on precision.[42] Probably biathletes cannot actively shoot between heart beats when the HR is 2-3 beats per second but the stroke volume is higher during shooting among biathletes than in rifle shooters and it would be interesting to know more about the effect that heart beats have on the movement of the rifle.

Biathletes often use their individually adapted breathing techniques[55] but how different breathing techniques affect shooting performance both in prone and standing shooting is not known. Therefore, studies using modern measurement tools for analysis of breathing technique in biathletes of different performance levels could provide important insights into these mechanisms of shooting performance.

Moreover, Vickers et al. found that gaze control is associated with shooting performance in biathlon[56] and found that basketball free throw performance increased after a period with quiet eye training.[56] To understand more about eye training for shooting performance could help athletes focus better and create a better understanding of how exercise might affect human perception.

A general investigation of the effect of course distance, altitude and wind conditions based on the race reports from IBU showed that these factors had an impact on performance (i.e. 2% slower per 1000 m altitude, 5% per extra average grade in the course profiles etc.) and that course speed was 2-3% faster in World Championships and Olympic Games than in the World Cup competitions.[54] To pace the races and find the best technical and tactical strategy for each competition venue could therefore improve performance. Therefore, more detailed pacing and technique analyses of biathlon World Cup races from different venues could also provide interesting knowledge for coaches and athletes, especially since there are many championships that will be arranged in altitude in the future (i.e. Olympic Games in 2022 and 2026 among several World Championships in biathlon).

In addition, several studies of brain activity during shooting have revealed associations between certain brain activity and performance,[57-59] but studies on the cognitive side of shooting directly after exercise of close to maximal intensity (i.e. questionnaires investigating what the best athletes in the biathlon World Cup are consciously focusing on before and during shooting), are lacking.

Finally, the IBU has in accordance with European Union regulations, banned fluor as a product that waxers can use underneath the skis for better glide. The effect of this ban might alter the competition times when waxers need to use other products and could therefore influence the effect of the different race components on overall performance.

Conclusions

In conclusion, this thesis reveals that in World Cup sprint races course time is the most important race component, explaining approximately 60% of the overall performance difference between a top 10 result and a result within rank 21 and 30. In World Cup individual races, course time and penalty time have similar importance, each explaining ~45-50% of the performance difference between a top 30 result and top 10. The most important component for performance in pursuit races is the start time, where more than 90% of top 3 results were achieved by the athletes starting as top 10 after the sprint race. Therefore, since course time is the most important component of sprint races, indirectly the impact of course time on overall performance in pursuit races might be underestimated when found to explain ~15% of overall performance. Indeed, start time explained 50% of the overall performance variance in pursuit races and considering the explanatory variables for overall performance in sprint races, the athletes are already ranked according to skiing speed when starting the pursuit.

In addition, men top 10 ski their races with an average speed approximately 12 % faster than women top 10 in sprint races and better performing biathletes pace their races more evenly, considering lap-to-lap-times.

In all event types a biathlete must hit more than 90% of the targets to be consistently within top 10 in the World Cup sprint, individual and pursuit races. The average hit percentages among top 10 results in these event types are 94-95% in prone and 90-91% in standing position among both men and women whereas top 30 athletes hit 89-90% in prone and 80-82% of the targets in standing. In other words, standing is the most performance differentiating of the two shooting positions.

In general, female biathletes use 6% more time during shooting than men and most of this time is lost to the first shots. Apart from the last standing shooting in individual races among top 10, there is no sex difference in shooting performance (i.e. number of targets hit), but male biathletes within top 10 in the individual distance miss the last shot in the last standing three times more often than any other standing shot whereas this did not occur among women.

Uphill performance (uphill sections each lasting from 22-85s) explains most of the variance in course time. RPE and %HRmax at submaximal stages while roller skiing in different sub-techniques were significantly associated with overall performance, and longer time to exhaustion in an all-out-test at 14% elevation was significantly correlated to shorter course times on the last lap in a biathlon sprint race. These findings validate simply measured performance-variables on submaximal stages on a treadmill as indications of progress for biathlon performance.

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Appendix A

The calculations of the normalized variables in study III in the pursuit distance. Time behind winner and “race time behind fastest race time” were used as dependent variables for the overall performance and isolated pursuit race (iso) performance analyses in the regression models.

Year	nt number	erall rank	Total time (s)	Start time (s)	Penalty time (s)	Course time (s)	Range time (s)	Shootti me (s)	Range time excluding shooting time (s)	misses (n)	Start number (n)	Course rank (n)	Time behind winner (s)	Start time behind winner (s)	Course time behind winner (s)	Penalty time behind winner (s)	Shooting time behind winner (s)	Range time behind winner (s)	Isolated pursuit race time (s)	Time behind iso (s)	Start time behind iso (s)	Course time behind iso (s)	Range time behind iso (s)	Shooting time behind iso (s)	Penalty time behind iso (s)	Miss1	Miss2	Miss3	Miss4
2015	1	1	1882.4	0	93.9	1594.9	193.6	118.8	74.8	3	1	12	0.0	0.0	0.0	0.0	0.0	0.0	1882.4	83.1	-140	48.2	-5.1	13.5	26.5	1	0	1	1
2015	1	2	1917.5	52	47.9	1628.9	188.7	112.4	76.3	1	2	41	35.1	52.0	34.0	-46.0	-6.4	1.5	1865.5	66.2	-88	82.2	-3.6	7.1	-19.5	0	1	0	0
2015	1	3	1937.6	64	72.1	1614.0	187.5	109.9	77.6	2	4	29	55.2	64.0	19.1	-21.8	-8.9	2.8	1873.6	74.3	-76	67.3	-2.3	4.6	4.7	0	0	1	1
2015	1	4	1939.3	140	67.4	1546.7	185.2	105.3	79.9	2	29	1	56.9	140.0	-48.2	-26.5	-13.5	5.1	1799.3	0	0	0	0	0	0	1	0	1	0
2015	1	5	1941.4	71	93.9	1588.4	188.1	111.2	76.9	3	7	11	59.0	71.0	-6.5	0.0	-7.6	2.1	1870.4	71.1	-69	41.7	-3	5.9	26.5	0	2	0	1
2015	1	6	1944.0	69	91.6	1584.5	198.9	120.1	78.8	3	5	7	61.6	69.0	-10.4	-2.3	1.3	4.0	1875	75.7	-71	37.8	-1.1	14.8	24.2	0	0	2	1
2015	1	7	1948.1	144	45.2	1568.5	190.4	115.3	75.1	1	34	3	65.7	144.0	-26.4	-48.7	-3.5	0.3	1804.1	4.8	4	21.8	-4.8	10	-22.2	0	0	1	0

Study I

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Study III

PLOS ONE

RESEARCH ARTICLE

Contribution from cross-country skiing, start time and shooting components to the overall and isolated biathlon pursuit race performance

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Abstract

Purpose

Biathlon is an Olympic sport combining 3–5 laps of cross-country skiing with rifle shooting, alternating between the prone and standing shooting positions between laps. The individual distance and the sprint are extensively examined whereas the pursuit, with start times based on the sprint results, is unexplored. Therefore, the current study aimed to investigate the contribution from start time, cross-country skiing time, penalty time, shooting time and range time to the overall and isolated performance in biathlon World Cup pursuit races.

Methods

38 and 37 stepwise linear regression analyses for each of the races were performed, including 112 and 128 unique athletes where 20 and 13 athletes had more than 20 results within top 30 during the seasons 2011/2012-2015/2016 in men and women, respectively.

Results

Start time (i.e. sprint race performance) together with penalty time, explained ~80% of the performance-variance (R^2) in overall pursuit performance in most races ($p<0.01$). For isolated pursuit performance, penalty time was the most important component, explaining >54% of the performance-variance in the majority of races, followed by course time (accumulated R^2 = .91-.92) and shooting time (accumulated R^2 = .98-.99) ($p<0.01$). Approximately the same rankings of factors were found when comparing standardized coefficients and correlation coefficients of the independent variables included in the regression.

Conclusion

Start time (i.e. sprint race performance) is the most important component for overall pursuit performance in biathlon, whereas shooting performance followed by course time are the most important components for the isolated pursuit race performance.

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(2016), and permission to use the data for scientific purposes was given by the IBU. Link: https://biathlonresults.com/. Permission to use the data for scientific purposes was granted by the IBU secretary general at the time. Due to the data being owned by IBU, other authors are encouraged to contact IBU for the possibility to analyze biathlon race results. Informed consent from the athletes was not necessary to collect, due to the data being publicly available.

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Introduction

Biathlon is an Olympic sport combining 3–5 laps of cross-country skiing with rifle shooting, alternating between the prone and standing shooting positions between laps. Several different biathlon events exist, in which the individual distance was included as an official World championship-event in 1958, followed by the relay (1960), sprint (1974), pursuit (1997), mass start (1998), mixed relay (2005) and the single mixed relay (2015) [1]. Among the four individual-start formats in biathlon, the individual distance and the sprint are extensively examined, [2–5] whereas the pursuit and the mass start races are almost unexplored [6, 7], although they comprise 50% of the individual-start race formats in the Olympics. In pursuit races, the 60 best athletes from the sprint race chase the leader over 12.5 and 10.0 km for men and women, respectively. The start time in the pursuit race is identical to the result of the sprint race performed 1–3 days before. The pursuit includes two prone and two standing shootings where the penalty loop is the same as for sprint races (150 m/22-24 s for both men and women).

The contribution from the different performance factors in biathlon have been analyzed both for the sprint race and the individual distance. In the sprint, around 60% of the performance difference between those finishing top 10 (G1-10) and those finishing among rank 21–30 (G21-30) was explained by cross-country skiing time (course time) and nearly 40% by shooting performance (i.e. penalty time) in both men and women [5]. The corresponding numbers for the individual distance showed that close to 50% of the overall performance was explained both by cross-country skiing time and shooting performance [3]. These differences between the two disciplines are expected due to the greater penalty for each miss in the individual distance compared to the sprint (i.e. 1 min versus 22–24 s), which is only partly compensated for by the 20% longer lap distance between shootings in the individual distance. In both cases, range time (time on the shooting range when excluding shooting time) and shooting time (time from approaching the shooting mat until the last shot hits the target) explained less than 3% of the performance-difference between G1-10 and G21-30. However, similar analyses for pursuit races do not exist, even though the pursuit differs markedly from other biathlon events since the start time for each athlete is based on the initial sprint race performance. In addition, the pursuit has higher frequency of shootings for each km of skiing compared to other events. The contribution from starting time to the overall performance as an additional main variable may change the impact of cross-country skiing time, shooting performance, shooting time and range time compared to the other events.

In addition, tight duels at the shooting range and the subsequently increased emotional pressure [8] may influence shooting times and range times differently than for races with an interval-start procedure, which could make the shooting component (shooting performance, shooting- and range-time) more important for overall performance and especially for the isolated pursuit performance. The rationale behind this hypothesis is that the shooting component (including shooting time, range time and penalty time) is of higher importance in pursuit races with shorter laps of skiing between shootings than in the sprints and individual distances. In addition, clean shooting and a fast range and shooting time could benefit the cross-country skiing time on the following lap, for example by gained position and positive effects of drafting within a group of athletes. Thus, the understanding of how the main components contribute to overall performance in the pursuit race (including start time/sprint race performance), as well as the contribution of the various components for the isolated pursuit race performance (excluding start time), is of high interest for coaches, athletes, media and the International Biathlon Union (IBU) which governs and organizes international biathlon events.

Therefore, the current study aimed to investigate the contribution from start time, cross-country skiing time, shooting performance, shooting time and range time to the overall and isolated performance in biathlon World Cup pursuit races in men and women. Due to the impact of start time (i.e. sprint performance) and the high frequency of shootings per distance skied, we hypothesized that start time and penalty time would explain the majority of performance variance in pursuit races for both men and women.

Methods

This study is based on publicly available race reports and results from the International Biathlon Union (IBU) datacenter (2016), with permission to use the data for scientific purposes given by IBU. A summary of the races included can be found in Table 1.

Statistical analyses

All statistical analyses were performed using SPSS statistics vs. 23.0, and data were tested for normality using the Shapiro-Wilk test and visual inspection. Data are presented as mean (95% CI).

Stepwise linear regression with total time behind the overall winner (including start time) and total time behind the fastest athlete in the isolated pursuit race (excluding start time) as dependent variables, and course time penalty time, shooting time and range time behind or ahead the overall winner and the fastest athlete in the race as independent variables were performed. The models were applied for top 30 athletes in pursuit races during the seasons 2011/2012-2015/2016. To analyze the importance of the different shootings for the overall penalty time, stepwise linear regression with total penalty time as dependent variable and penalty time from each of the four shootings as independent variables was applied. For the stepwise multiple regressions, outliers and extreme values were defined using boxplots with the range between 1st and 3rd quartile cutoffs (i.e. 50% of the data lies within the 1st and 3rd quartile) as reference values. An outlier was defined as being 1.5 times this range away from either of these quartile cutoffs, and extreme values were defined as being more than 3.0 times the range of the 1st and 3rd quartile-box away from the 1st or 3rd quartile data-points. This procedure removed 99 outliers or extreme values out of 1140 results among men and 78 out of 1110 results among women, in which five winners and two 2nd places were removed from the men's races and 8 winners and three 2nd places were removed from the women's races. Removal of the outliers and extreme values only affected the stepwise regressions and correlation analyses and were included for the simple summation of start number and overall rank and the analyzes of overall and isolated pursuit race winners in the results section. Significant multicollinearity between a few independent variables in some of the races were found, but the correlation

Table 1. Number of races, unique athletes and the average (95% confidence interval) race distance, maximum climb, total climb, air temperature and humidity.

	Men	Women
Number of races	38	37
Unique athletes	112	128
Unique athletes with >20 results within top 30	20	13
Race distance (m)	12740 (12663,12818)	10396 (10338,10454)
Maximum climb (m)	25 (22,29)	21 (19,24)
Total climb (m)	83 (80,86)	64 (60,67)
Air temperature (˚C)	-0.6 (-2.5,1.4)	-0.6 (-2.5,1.4)
Humidity (%)	70 (64,76)	70 (63,76)

Race distance refers to the total distance from start to finish, including the shooting range.

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coefficients of these associations were relatively low (mostly 0.3–0.4 and never above 0.6). Although the results of the linear regression analyses must be interpreted with this in mind, we argue that the multicollinearity between independent variables did not affect the conclusions of our study. This is supported by the consistent findings across the various analyses done in our approach.

In addition, independent samples t-tests were used to analyze sex differences in start time, course time, skiing speed, shooting time and numbers of places climbed between men and women both for the overall performance and for time within the isolated pursuit race.

Results

The average overall racing times (including start time) were 34:20 min (95%CI: 33:50,34:50) and 33:08 min (32:30,33:46), with average isolated pursuit race times of 33:16 min (32:46,33:46) and 31:56 min (31:21,32:32) among top 30 for men and women, respectively. This corresponds to average start times behind the winner of 1:04 min (1:00,1:09) and 1:12 min (1:06,1:17) for men and women, respectively. Out of 20 shots, the average number of misses at the shooting range were 2.6 (2.4,2.8) and 2.8 (2.6,3.1) in each competition among top 30 for men and women, respectively.

Overall performance

The average total times of the winners were 32:47 min (32:18,33:16) and 30:57 min (30:27, 31:27), with average isolated pursuit race times of 32:35 min (32:06,33:04) and 30:44 min (30:12,31:16) in men and women, respectively.

The overall winner had the fastest race time in the isolated pursuit race in 9% and 13% of the races among men and women, respectively. On average, overall winners started 11.6 s (6.5,16.8) and 13.7 s (8.2,19.3) behind the winner of the sprint in men and women, respectively, with a median start number of 2 among both sexes. In 37% and 32% of the races among men and women, respectively, the overall winner was also the winner of the sprint race. In all except one race, the overall winner started as number 10 or better in both sexes, with 84% and 81% of all victories being achieved by athletes starting as number 5 or better among men and women (Fig 1). However, in 50% of the pursuit races the winner of the sprint ended up more than 51 and 58 seconds behind the overall winner in men and women, respectively, and had the fastest isolated pursuit race time in only one race among both sexes.

Pearson correlation analyses showed that start time correlated most frequently with overall performance in pursuit races (Table 2) followed by penalty time and course time among both men and women.

The results from the stepwise multiple regression analyses are shown in Table 3. The analyses show that start time explained 50–51% of the variance in time behind the overall winner in the 23 and 22 races among men and women, respectively. When additionally including penalty time, the model explained 78–80% of the variance in time behind the overall winner in both sexes.

In addition to the results in Table 3, three races among men and two races among women had best fit for other models with various rankings of the different variables. In one race among men, no variables correlated with overall performance.

The stepwise linear regression with total penalty time as dependent variable showed standing shootings to explain 70–90% of the variance in total penalty time within both sexes, with no difference in the importance from shooting 3 and 4.

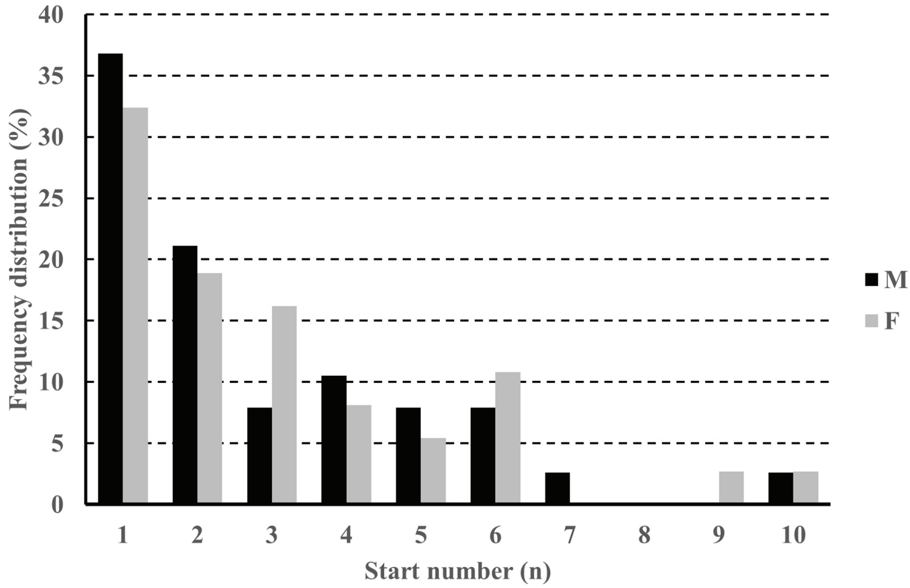

Fig 1. The distribution of overall pursuit winners in biathlon for the different start numbers in the race (i.e. based on results of the sprint race) in the seasons 2011–2015 in men (M) and women (W).

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Isolated pursuit race performance

The median start number of athletes having the fastest isolated pursuit race times were 19 and 12, among men and women, respectively. This corresponded to 1:05 min (:54,1:17) and :52 min (:41,1:04) behind the winner of the sprint race and ended up finishing top 5 overall in the pursuit race in 76.3% and 86.5% of the races among men and women, respectively. Here, we found a significant sex difference in start number ($p<.05$) but not in start time ($p = .105$). On average, the fastest isolated race time among men gave a final rank [2.9 (2.0,3.8)] closer to the overall victory than among women [4.3 (3.3,5.3), $p<.05$]. In only 7.9% and 2.7% of the races,

Table 2. The average correlation coefficients and the number of races with significant positive or negative correlations between time behind the overall pursuit race winner and start, penalty, course, shooting and range time behind the overall winner.

Overall pursuit race time behind*	Men				Women	
Variable	Number of positive correlations	Average of the positive correlations	Number of negative correlations	Average of the negative correlations	Number of positive correlations	Average of the positive correlations
Start time (s)	35	.61			37	.64
Penalty time (s)	35	.46			34	.45
Course time (s)	26	.52			30	.55
Shooting time (s)	17	.42			7	.43
Range time (s)	6	.36	3	-.38	13	.45

*Time behind the overall pursuit race winner was correlated with time behind the overall winner for each of the listed variables. Only significant correlations for each variable were included in the table.

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Table 3. Summary of the stepwise multiple regression analyses performed individually for each race with total time behind the overall winner as dependent variable.

	Men		Women	
Total number of races included	**38**		**37**	
	Model outcome 1			
Number of races with best fit	23	B stand	22	B stand
1. Start time	49.7 (42.8,56.6)	.73	50.9 (44.0,57.8)	.64
2. Penalty time	79.8 (75.5,84.2)	.68	78.1 (74.4,81.9)	.70
3. Course time	96.1 (95.4,96.8)	.47	95.4 (94.3,96.5)	.54
4. Shooting time	99.6 (99.4,99.8)	.22	99.8 (99.6,100)	.24
	Model outcome 2			
Number of races with best fit	7	B stand	4	B stand
1. Penalty time	40.0 (26.5,53.5)	.84	41.3	.70
2. Start time	76.7 (66.9,86.5)	.73	73.3	.54
3. Course time	92.0 (85.2,98.8)	.48	94.0	.57
4. Shooting time	99.6 (99.1,100.0)	.30	99.5	.24
	Model outcome 3			
Number of races with best fit	1	B stand	5	B stand
1. Course time	40.2	.49	50.0 (38.5,61.5)	.59
2. Penalty time	73.0	.59	72.8 (66.0,78.7)	.65
3. Start time	97.4	.52	95.8 (94.0,97.6)	.55
4. Shooting time	99.5	.18	99.8 (99.2,100.0)	.23
	Model outcome 4			
Number of races with best fit	3	B stand	3	B stand
1. Start time	55.6	.72	59.6	.63
2. Course time	73.4	.55	78.4	.57
3. Penalty time	94.7	.63	97.4	.51
4. Shooting time	99.4	.28	99.8	.17

Each model lists average cumulated $R^{2*}100$ (including 95% confidence intervals when more than 4 races fit the regression). Start, penalty, course, shooting and range time behind the overall winner were used as independent variables. Each model includes the races where the indicated ranking of the different components [from most (1) to least (4) influential] provided the best fit to the regression. B stand = average of the standardized coefficients.

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the athlete with the fastest race time ended up outside of top 10 among men and women, respectively. The average number of misses were lower in men [.79 (.53,1.04)] than in women [1.22 (.93,1.50), $p < .05$], and in 39.5 and 21.6% of the cases, the fastest athlete in the isolated pursuit race missed zero shots, whereas 84.2 and 62.2% hit 19 or 20 out of the 20 shots among men and women, respectively. In addition, 50.0% and 70.3% of the fastest isolated race time-results in men and women, respectively, were among the five fastest in course time in these competitions.

Out of the five main variables, penalty time correlated most strongly with total time behind the fastest isolated race time (Table 4) and correlated significantly with the fastest isolated pursuit race time in all races ($p<.05$).

Results from the stepwise regression analyses, with time behind the fastest isolated pursuit race time as dependent variable, shows that penalty time is the most important component, followed by course time and shooting time in most of the races (Table 5).

In addition to the results in Table 5, two races among women had best fit for models with other rankings of the variables.

Table 4. The average correlation coefficients and the number of races with significant positive or negative correlations between time behind the fastest isolated pursuit race time and start, penalty, course, shooting and range time behind the athlete with the fastest isolated pursuit race time.

Isolated pursuit race time behind*	Men				Women			
Variable	Nr. of positive correlations	Avrg. of the positive correlations	Nr. of negative correlations	Avrg. of the negative correlations	Nr. of positive correlations	Avrg. of the positive correlations	Nr. of negative correlations	Avrg. of the negative correlations
Penalty time* (s)	38	.76			37	.68		
Course time* (s)	28	.51			30	.51		
Start time* (s)	1	.35	11	-.44	6	.40	3	-.41
Shooting time* (s)	12	.44			7	.43		
Range time* (s)	1	.32	1	-.36	6	.40	1	-.32

*Time behind the fastest athlete in the isolated pursuit race was correlated with the time behind the athlete with the fastest isolated pursuit race time for each of the listed variables. Only significant correlations for each variable were included in the table.

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Discussion

This study investigated the contribution from start time, cross-country skiing performance and shooting performance in biathlon World Cup pursuit races, as well as these factors' importance to isolated pursuit race performance. The main findings show that in 60% of the races, start time (i.e. sprint race performance) was the most important component, explaining approximately 50% of the variance in overall performance among both men and women. This was followed by penalty time, which together with start time explained approximately 80% of the overall performance in both sexes. When further adding course time in the regression

Table 5. Summary of the stepwise multiple regression analyses performed individually for each race with total time behind the isolated pursuit race winner as dependent variable.

	Men		Women	
Total number of isolated pursuit race performances included	**38**		**37**	
		Model outcome 1		
Number of races with best fit	35	B stand	27	B stand
1. Penalty time	61.7 (57.4,66.0)	.87	54.1 (49.2,59.0)	.90
2. Course time	91.7 (90.5,93.0)	.59	91.1 (89.4,92.8)	.70
3. Shooting time	99.0 (98.8,99.3)	.29	99.3 (99.0,99.6)	.31
4. Range time	100	.11	100	.09
		Model outcome 2		
Number of races with best fit	3	B stand	8	B stand
1. Course time	45.0	.80	44.1 (33.3,55.0)	.85
2. Penalty time	91.7	.92	92.0 (88.6,95.4)	.84
3. Shooting time	98.3	.32	99.1 (98.3,100.0)	.30
4. Range time	100	.14	100	.10

Each model lists average cumulated $R^{2}*100$ (including 95% confidence intervals when more than 4 races fit the regression). Penalty, course, shooting and range time behind the isolated pursuit race winner were used as independent variables. Each model includes all races where the indicated ranking of the different components [from most (1) to least (4) influential] fit the model best. B stand = average of the standardized coefficients.

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analyses, the model explained 95–96% of the variance in overall performance in both men and women. In addition, analyses of the isolated pursuit race performance showed that in 92 and 73% of the races among men and women, respectively, penalty time was the most important component followed by course time and shooting time, explaining >54, 91–92 and 98–99% of the performance-variance. Both for overall and isolated pursuit race performance, approximately the same rankings of factors were found when comparing standardized coefficients and correlation coefficients of the independent variables included in the regression.

Overall performance

Our analyses show that start time, that is sprint race performance, is the most important component for the overall pursuit race performance. Above 80% of the overall winners started as number 5 or better after the sprint among both men and women, and the regression analyses show that in 23 and 22 races out of the 38 and 37 pursuit races investigated in men and women, respectively, 50% of the overall performance is explained by start time. Altogether this highlights the importance of the sprint race to the overall pursuit race performance in biathlon.

Penalty time was ranked as the second most contributing component in 23 and 22 races of the pursuit races. Regression analyses showed that start time and penalty time together explained approximately 80% of the overall performance in these races. In 7 and 4 races among men and women, respectively, penalty time was ranked as the most important component, with regression analyses showing that approximately 40% of the overall pursuit performance variance was explained by penalty time in both men and women. Our findings also show that winners of pursuit races very rarely have more than 2 misses, that mostly occur in the standing shootings which also explains most of the variance in penalty time. In addition, there was no sex difference in penalty time among top 30 athletes. This is in line with previous findings in sprint showing that top 10-athletes in sprint races on average hit more than 90% of the targets, where most of the misses occur during standing shooting and that there is no sex difference in shooting performance within top 30 [5]. Together with the large standardized coefficients and high frequency of significant correlations between penalty time and overall performance, this emphasizes the importance of the shooting component and especially performance in the standing shootings to overall pursuit race performance.

Course time was the third most important component in most of the pursuit races, where the regression analyses showed that the model increased its explanatory fit from approximately 80% with start and penalty time included in the model, to more than 95% when course time was included. The relatively low importance of course time compared to start time and penalty time might be explained by the advantage of skiing in a group, because of drafting that is often the case in pursuit races. This would logically make the start time and penalty time more important since athletes who are originally faster skiers have difficulties breaking away from a group and slower skiers can join groups of skiers that are normally faster in individual-start races. In addition, the athletes starting early in the pursuit race might use a more conservative pacing strategy to prepare for shooting in the beginning of the race compared to those chasing from behind. This corresponds with more even pacing, as shown previously for better performing athletes in biathlon sprint races [9].

Shooting time was ranked as the fourth most contributing component in almost all races, explaining on average 3–7% of the performance-variance. This is more than previously found for the sprint and individual distance, which makes sense because the frequency of shootings relative to the skiing distance in pursuits is higher [10]. Furthermore, fast shooting probably provides an advantage in duel shooting to climb places compared to events with interval-start procedure. In their review of the scientific literature in biathlon, together with analyses of the Olympic biathlon events in Pyeongchang, Laaksonen et al. [10] suggested that fast and clean shooting (no mistakes) would become even more important to win future biathlon races.

Range time contributed significantly to the overall performance in only one of the 38 races among men and in none of the races among women. This is in contrast to research from 1992, that indicated that biathletes could save approximately 10 s in range time by maintaining speed in the last 50 m before shooting [11]. This is no longer the case either in the sprint [5], individual [3], and according to the present results, in pursuit races.

Isolated pursuit race performance

Since start time (i.e. the previous sprint race performance) explains 50% of the variance in overall performance within both men and women in most of the races, it is of further interest to understand how the different components contribute to the isolated pursuit race (i.e. when excluding start time). Our analyses show that penalty time is the most important component for the isolated pursuit race performance in almost all races among men and in around 80% of races among women, explaining approximately 62 and 54% of the variance in race time in men and women, respectively.

Course time was the second most important component for the isolated pursuit race performance, which together with penalty time explains more than 90% of the performance-variance in isolated pursuit races. The fastest isolated pursuit race times among women are to a greater extent than among men explained by faster skiing and to a lesser extent by shooting performance. This indicates a greater opportunity for faster skiers in the women's class to climb ranks in the pursuit race.

Shooting time was more important for the isolated pursuit race performance than for the overall pursuit race performance, explaining approximately 8% of the variance in isolated pursuit race time in both men and women. This means that shooting time is an important component for the isolated pursuit race performance. Together, the importance of penalty time and shooting time highlights the high importance of the shooting component for the isolated pursuit race performance, as it explains approximately 60–70% of the performance-variance in both sexes. In addition, the fastest athletes in the isolated pursuit race among women tended to shoot slower than men, in line with previous research on the sprint and individual distances [3, 5, 10, 12], indicating that there is more to gain in shooting time among women than among men.

Start time correlated negatively with isolated pursuit performance in 11 races among men and in 3 races among women, which suggests that start time provides a larger advantage for women than for men. This could be related to the larger time-gap between athletes after the sprint race in the women's class compared to men.

The size of the standardized coefficients in the regression analyses and the frequency and strength of significant correlations between the various independent variables and pursuit performance shows a similar picture as the regression analyses. Although this study indicates that shooting is more important in pursuits than in sprint races, start time explains a large portion of performance in biathlon pursuit races. Thus, the same components as for the sprint distance should also be emphasized when training for the pursuit. However, our analyses show that the fastest athletes in the isolated pursuit race, started on average as number 20 and 14 and ended up finishing top 5 overall in 76 and 87% of the races among men and women, respectively. In addition, the winner of the sprint race rarely had the fastest isolated pursuit race time and in half of the races ended up approximately 1 minute behind the overall winner. Furthermore, penalty time explains most of the variance for the isolated pursuit race result in most of the races in both sexes. In addition, most of the variance in penalty time was explained by the two last shootings in pursuit races for both sexes. Therefore the uncertainty in outcome, which is important in competitive sports [13], is maintained until the last shootings in the pursuit in biathlon. This factor has likely also contributed to the increase in popularity of biathlon [13], with a race format leading to tight duels at the shooting range where the first athlete to cross the finish line is the overall winner. While the same factors generally contribute to performance in both sexes, the current and previous results indicate that coaches and athletes should be aware of the different performance demands in the men's and women's class and especially consider the possibility for shooting faster among women.

Methodological considerations

We argue that the analyses of all 38 and 37 races provides a good overall picture on the most important race components contributing to overall and isolated pursuit race performance. However, the effect of course profile, weather conditions and other factors such as mental pressure in Championships would be logical explanatory factors for the within-race differences that should be considered when analyzing single races.

For the stepwise regression analyses, each race was analyzed individually and for this reason the model outcomes cannot be generalized to all races. However, supporting the stepwise regression analyses employed here, our analyses of standardized coefficients together with the simple descriptive statistics and correlational analyses supported the main findings outlined. Thus, we argue that these findings together provide a comprehensive picture of the importance of cross-country skiing, start time and shooting components to the overall and isolated biathlon pursuit race performance.

Significant multicollinearity between a few independent variables in some of the races were found, but the correlation coefficients of these associations were relatively low (mostly 0.3–0.4 and never above 0.6). Although the results of the linear regression analyses must be interpreted with this in mind, we argue that the multicollinearity between independent variables did not affect the conclusions of our study. This is supported by the consistent findings across the various analyses done in our approach.

Shooting times are extracted from the range times based on the manual recordings of shooting time and shooting time and range time data are therefore not highly accurate. However, this error is random and unlikely to influence the conclusions in our approach. Still, some caution should be made when interpreting the results of the present study.

Conclusions

Start time is the most important component for overall pursuit performance in biathlon, demonstrating that performance in the preceding sprint race is the most important component in the biathlon pursuit. This is followed by penalty time as the second most contributing component, which together with start time explain approximately 80% of the variance in overall pursuit race performance in both men and women. When excluding start time, penalty time is the most important component of the isolated pursuit race performance in almost all races among men and in most races for women, with course time being the second most important component.

Supporting information

S1 File.
(XLSX)

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Analysis of a Biathlon Sprint Competition and Associated Laboratory Determinants of Performance

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Biathlon is an Olympic winter-sport where cross-country (XC) skiing in the skating technique is combined with rifle shooting. In the biathlon sprint competition for men, three laps of 3.3-km are interspersed with a 5-shot shooting sequence in the prone and standing position. Our purpose was to investigate the contribution from overall XC skiing performance, the performance in different terrain sections and shooting performance to the overall biathlon sprint race performance, as well as the relationship to laboratory-measured capacities obtained during treadmill roller ski skating. Eleven elite male biathletes were tracked by a Global Positioning System (GPS) device and a heart rate (HR) monitor during an international 10-km biathlon sprint competition. Within a period of 6 weeks prior to the competition, physiological responses, and performance during submaximal and maximal treadmill roller skiing were measured. Stepwise multiple regression analysis revealed that XC skiing time, shooting performance, shooting time and range time explained 84, 14, 1.8, and 0.2% of the overall sprint race performance (all $p < 0.01$). Time in uphill, varied, and downhill terrains were all significantly correlated to the total XC skiing time ($r = 0.95$, 0.82, 0.72, respectively, all $p < 0.05$). Percent of maximal HR (HRmax) and rating of perceived exertion (RPE) during submaximal roller skiing, and time-to-exhaustion during incremental roller skiing correlated significantly with overall biathlon sprint race performance and overall XC skiing time ($r = 0.64$–0.95, all $p < 0.05$). In conclusion, XC skiing performance provided greatest impact on biathlon sprint performance, with most of the variance determined by XC skiing performance in the uphill terrain sections. Furthermore, the ability to roller ski with a low RPE and %HRmax during submaximal speeds, as well as time-to-exhaustion during incremental roller skiing significantly predicted biathlon performance. Such laboratory-derived measures may therefore be validly used to distinguish biathletes of different performance levels and to track progress of their XC skiing capacity.

Keywords: biathletes, cross-country skiing, gross efficiency, maximal oxygen uptake, rifle shooting

INTRODUCTION

Biathlon is an Olympic winter-sport with two main components; cross-country (XC) skiing in the skating technique combined with 5-shot rifle shooting sequences. For men, the biathlon sprint competition consists of three laps of 3.3 km interspersed with shooting in the prone and standing position, in which each missed shot is penalized by adding a 150-m XC skiing loop (IBU, 2017). Shooting is performed on a 50 m shooting range using 0.22 caliber long rifles weighing >3.5 kg that the athletes carry on their back while skiing, and the circular hit areas are 45 mm in diameter in prone and 115 mm in standing shooting. Thus, success in biathlon demands high aerobic endurance capacity, an efficient skiing technique, as well as rapid and accurate shooting performed directly after high-intensity exercise.

A recent investigation of World Cup performance in biathlon sprint events shows that XC skiing time is the most distinguishing factor for the overall performance (Luchsinger et al., 2018), explaining ∼59–65% of the overall performance difference between top-10 results and those finishing among 21–30 in both sexes. Furthermore, ∼31–35% of the group-difference was explained by shooting performance (i.e., time spent in the penalty loop due to missed targets), whereas shooting time and range time (i.e., time at the shooting range minus shooting time) together explained only 4–6% of the group-difference in overall biathlon sprint performance. This is supported by the work of Skattebo and Losnegard (2017) where the largest between-athlete variability was found for XC skiing time followed by shooting performance during biathlon sprint races.

Although the scientific understanding of XC skiing demands is relatively well-defined (Sandbakk and Holmberg, 2014, 2017; Losnegard, 2019), a more comprehensive understanding of the demands of XC skiing performance in biathlon is needed. In their review of the scientific literature in biathlon, Laaksonen et al. (2018a) wrote that the forced breaks (when shooting) between bouts of close to maximal intensity skiing is unique in endurance sports. More accurate analyses of the skiing component of biathlon races can be gained by combining wearable Global Positioning Systems (GPS) with heart rate (HR) monitoring during competitions. However, while this methodology has not yet been employed in biathlon events for scientific purposes, the many GPS-based studies performed in XC skiing have revealed that more than 50% of the total race time is spent uphill and that these terrain sections are most performance-differentiating (Andersson et al., 2010; Bolger et al., 2015; Sandbakk et al., 2016b; Solli et al., 2018). Although the physiological demands of the XC skiing component of biathlon competitions are comparable to those seen in XC skiing, biathletes compete only in the skating technique and with a rifle carried on the back that alters the energy cost and kinematical aspects of skiing (Stöggl et al., 2015). In addition, biathletes' pacing strategies need to take into account the important 25–30 s shooting sequences during the competition (Laaksonen et al., 2018b). Therefore, biathletes may use less effort on uphill terrain sections to avoid accumulation of fatigue when approaching the shooting range.

In addition, knowledge about the underlying laboratory-measured performance-determinants for XC skiing performance in modern biathlon sprint races are lacking. XC skiing performance has previously been linked to peak oxygen uptake (VO_{2peak}) and the ability to effectively convert metabolic energy into external work rate and speed [i.e., gross efficiency (GE)] in XC skiers (Sandbakk et al., 2010, 2011b, 2013, 2016a,b) and Nordic combined athletes (Sandbakk et al., 2016c; Rasdal et al., 2017). This has provided coaches and athletes with valuable insight into the relationships between competition performance and different performance-indices obtained in the laboratory. However, the current knowledge on the importance of these factors in biathlon is scarce, and their association to performance has not been studied since the mid-1990s (Rundell, 1995; Rundell and Bacharach, 1995).

On this basis, the present study aims to investigate the contribution from overall XC skiing performance, performance in different terrain sections, and shooting performance to the overall biathlon sprint race performance. In addition, we aim to examine the relationships between overall biathlon and XC skiing performance to laboratory-measured capacities obtained during treadmill roller skiing. We hypothesize that XC skiing performance on uphill terrain provides the strongest relationships with overall biathlon sprint performance, and that uphill performance would correlate strongly with VO_{2peak} and gross efficiency while treadmill roller skiing.

TABLE 1 | Characteristics (mean ± SD) of the eleven elite male biathletes participating in the study.

Age (yrs)	21.4 ± 2.1
Body height (cm)	181.1 ± 4.7
Body mass (kg)	76.5 ± 4.8
Body mass index ($kg \cdot m^{-2}$)	23.5 ± 1.3
Rifle weight (kg)	4.0 ± 0.3
Annual training[a] (hrs)	685 ± 115
Physical training[a] (hrs)	585 ± 87
Shooting training[a] (hrs)	100 ± 34
Maximum HR[b] ($beats \cdot min^{-1}$)	198 ± 8

[a] *Training volume categorized into hours of total training, physical training and shooting training during the last 12 months prior to the competition.*
[b] *Self-reported maximum heart rate (HR_{max}) based on outdoor tests from the year prior to this study.*

METHODS

Participants

Eleven elite male biathletes, members of the junior and recruitment team of the Norwegian Biathlon Association, competing in the IBU-cup, Jr. World championships and at the highest level in the Norwegian cup, volunteered to participate in the study. The participant's age, anthropometrics and training characteristics are presented in **Table 1**.

Ethics Statement

The Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for this study. Therefore, the ethics of the study is done according to the institutional requirements and approval for data security and handling was obtained from the Norwegian Centre for Research Data. Prior to the data collection, all participants provided written informed consent to voluntarily take part in the study. The participants were informed that they could withdraw from the study at any point in time without providing a reason for doing so.

Overall Design

During an international 10-km biathlon sprint competition in mid-November 2016, regulated by the International Biathlon Association (IBU), all study participants were tracked by a GPS device and HR monitor. The racecourse was mapped with a coupled GPS and barometer to provide a valid course and elevation profile. The XC skiing course was further divided into uphill, varied, and downhill terrain sections, and the overall shooting component was separated into range time (time spent at the shooting range excluding shooting time), shooting time and penalty time (time spent in the penalty loop as a consequence of misses at the shooting range). Within a period of 6 weeks prior to the competition, all participants completed submaximal and maximal laboratory testing while roller skiing on a treadmill using different speed and incline combinations.

Laboratory Testing

Initially, the participants performed 15 min of low-intensity warm-up while roller skiing on the treadmill. The first 10 min of the warm-up were conducted without the rifle and the last 5 min while carrying the rifle on their back. Thereafter, the submaximal tests were performed consisting of two 5-min stages (one with and one without carrying the rifle) with 2-min recovery in-between using each of the three most important sub-techniques (G2–G4) in the skating technique (for a more detailed description of sub-techniques, see Andersson et al., 2010). The first two stages were conducted utilizing the G4 sub-technique at 3% inclination and 20 $km\cdot h^{-1}$, followed by two stages using the G3 sub-technique at 5% inclination and 15 $km\cdot h^{-1}$. The two last stages were performed with the G2 sub-technique at 12% inclination and a speed of 8 $km\cdot h^{-1}$, respectively. The inclines were based on previous research indicating which inclines the different sub-techniques are naturally employed. The speeds were chosen to match all inclines for metabolic cost, based on pilot tests of biathletes and XC skiers in our laboratory. Respiratory variables and HR were measured continuously and the average of the last 2 min of each stage was used for steady-state analyses. Blood lactate concentrations and RPE were determined directly after completing each submaximal stage. In the final analyses, only the measurements using the rifle were used. After a 5-min recovery period, all participants completed maximal roller skiing using an incremental test to exhaustion to determine VO_{2peak} and time to exhaustion (TTE; as a measure of performance). The starting incline and speed was 10% and 11 $km\cdot h^{-1}$. The initial speed was kept constant, while the incline was increased by 2%-points every minute up to 14%. Thereafter, the speed was increased by 1 $km\cdot h^{-1}$ every minute until exhaustion. Respiratory variables and HR were measured continuously and VO_{2peak} was defined as the average of the three highest and consecutive 10 s measurements. Peak HR (HR_{peak}) was defined as the highest 5 s HR measurement during the test. Blood lactate concentrations and RPE were measured directly after the maximal-test. Treadmill roller skiing was performed on a 5 × 3 m motor-driven treadmill (Forcelink B.V., Culemborg, The Netherlands) with non-slip rubber surface on the treadmill belt, allowing the participants to use their own poles with special carbide tips. To minimize variations in roller resistance, the participants used the same pair of skating roller skis with standard category 2 wheels (IDT Sports, Lena, Norway). Before the tests, rolling friction force (F_f) was tested with a towing test as previously described (Sandbakk et al., 2010). The rolling friction coefficient (μ) was determined by dividing F_f by the normal force ($F_n = F_f / F_n$), and provided an average μ value of 0.0195, which was included in the calculation of work rate. The biathletes used their own rifle with an average weight of 4.0 ± 0.3 kg during laboratory testing.

Respiratory variables were measured using open-circuit indirect calorimetry with mixing chamber and 30 s averages of the respiratory variables were used (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany). The instruments were calibrated against ambient air conditions and certified gases of known concentrations of O_2 (15.0%) and CO_2 (5.0%) before each test session. The flow transducer (Triple V, Erick Jaeger GmbH, Hoechberg, Germany) was calibrated using a 3-L high-precision calibration syringe (Calibration syringe D, SensorMedics, Yorba Linda, CA, USA). HR was continuously measured with a Polar V800 monitor and synchronized with the Oxycon Pro system. Blood lactate in 20 μL of blood was taken from the fingertip and measured using the stationary Biosen C-Line lactate analyzer (Biosen, EKF Industrial Electronics, Magdeburg, Germany). The device was calibrated every 60 min with a 12 $mmol\cdot L^{-1}$ standard concentration. Rating of perceived exertion (RPE) was determined using the 6–20 Borg Scale (Borg, 1982). The participants' body-mass and mass of the rifle were measured using a precise weight (Seca, model 708, GmbH, Hamburg, Germany), and body-height using a calibrated stadiometer (Holtain Ltd, Crosswell, UK), prior to the test.

Work rate was calculated as the sum of power against gravity and friction: $P_g + P_f = mgv\,[\sin(\alpha) + \cos(\alpha)\mu]$, with P_g being power against gravity, P_f power against friction, m the biathletes body-mass including skiing shoes, roller skis (and the rifle when roller skiing with the rifle), g the gravitational constant, α the treadmill incline, μ the frictional coefficient and v the treadmill speed. The aerobic metabolic rate was calculated as the product of VO_2 and the oxygen energetic equivalent using the associated respiratory exchange ratio and standard conversion tables (Peronnet and Massicotte, 1991). GE was defined as the ratio of work rate and aerobic metabolic rate and calculated from the submaximal tests (Sandbakk et al., 2010).

Competition Analysis

Prior to the competition, all the participants completed low-intensity warm-up procedures according to their own optimized protocols used in both training and competition. All participants used their own equipment during the competition, including rifle (4.0 ± 0.3 kg), poles (91 ± 1% of body height), skating XC skiing shoes, and skating XC skis. The

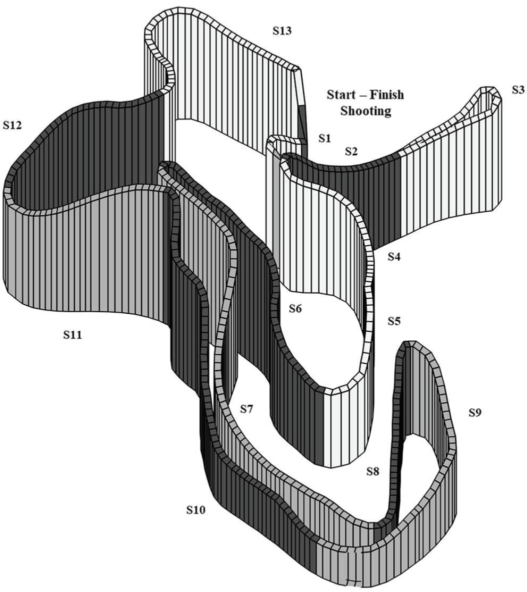

FIGURE 1 | 3D illustration of the 3015 m XC skiing racecourse divided into 13 different terrain sections. Detailed information about the terrain sections is described in **Table 3**.

skis were accustomed to individual preferences and prepared for the current conditions with appropriate ski base material and chamber stiffness. The weather conditions were stable throughout the entire competition with average ambient air and snow temperatures of −5.5 and −7.5°C, respectively. The average relative humidity was 85% during the competition and the wind was low and stable at the shooting range, varying between 0.3 and 1.0 m/s. Weather conditions were continuously registered during the competition using a weather station developed by the Norwegian Top Sport Centre (delivered by Airtight Ltd., Oslo, Norway), measuring both air and snow temperatures and humidity. Wind speeds during the competition were collected from the official shooting results (Biathlon, 2017). The racecourse consisted of a combination of artificial and natural snow and was machine-groomed the same morning as the competition day. The course was set in an open area with minimal tree cover and no steep mountains that could interfere with the GPS signals. Course and elevation profiles of the racecourse were measured with an integrated GPS and barometry using a Garmin Forerunner 920 XT (Garmin Ltd., Olathe, Kansas, USA), which collected position and altitude data at a 1 Hz sampling rate to define a reference course with accompanying altitude profile as previously described by Bolger et al. (2015) and Sandbakk et al. (2016b). The participants hit rate (number of targets hit) was provided by the official competition shooting results collected with an electronic target system (Megalink) (Biathlon, 2017). Penalty time was used as the measure of shooting performance in multiple regression and correlation analyses. The XC skiing course was divided into uphill, varied, and downhill terrain that equaled 37, 29, and 34% of the total course distance, respectively. A part of the XC skiing course prior to the shooting range was defined for analysis of pacing toward shooting. This part of the course included terrain section 12, defined as uphill, and section 13, defined as varied terrain (**Figure 1**, **Table 3**). In addition, each participant's time spent in this part toward shooting was divided by the total XC skiing time in uphill and varied sections on each lap for analyses of their relative time in this "preparation phase prior to shooting" compared to the rest of the course. The classification of different terrain sections was based on the International Ski Federation (FIS) homologation manual for XC skiing racecourses (FIS, 2017). A section boundary was defined where a change between positive and negative gradient in the XC skiing course profile occurred. Terrain sections with climb >10 m and gradient >6% were classified as uphill sections. Sections with descent >10 m and negative gradient >6% were classified as downhill sections. Remaining sections were classified as varied terrain, including short uphill and downhill sections interspersed with flat sections. A part of the racecourse, consisting of flat terrain in the start and finish of the competition, was not included in the final analysis to ensure that the start and final sprint would not affect the analyses of pacing strategies. The exact distance for each lap of the XC skiing racecourse was then 3,015 m.

During the competition, each participant was tracked by a Polar V800 GPS (Polar Electro Oy, Kempele, Finland), which collected position and HR data at a 1 Hz sampling rate. All GPS watches were turned on at least 30 min before the start of the race to ensure that the GPS watches could acquire contact with as many satellites as possible before race start, in order to optimize GPS accuracy for the duration of the race. Furthermore, data for all the participants were adapted to the reference course by fitting each competitors' GPS track to points along the reference course. This method, developed in cooperation between the national biathlon and XC ski federations, Norwegian Olympic Sports Centre and academic institutions provide sufficiently accurate data for the analyses needed here, amounting to a measurement error of up to ±1 s for each 180 m-split, when being compared to more accurate GPS-systems (Gløersen et al., 2018). Virtual split times were defined at every section boundary (uphill, downhill, varied terrain) along the course. Virtual split times in the shooting component were defined using a combination of GPS position and speed data. The time each participant spent in the different components of the race, as well as HR characteristics were calculated based on these virtual split times. Shooting time was defined as the time on the shooting range when speed was below 1.8 m/s (when athletes were at the shooting mat), whereas penalty time was defined as the time spent between a point after the range (i.e., before the penalty loop) and a point after the penalty loop. Thus, athletes with no mistakes also had a short penalty time. Range time was defined as the time spent at the shooting range, without shooting time.

Statistical Analysis

All data were tested for normality using a Shapiro–Wilk test in combination with visual inspection of data, and all variables are presented as mean ± SD. Correlations between overall biathlon sprint race performance and the different sections of the race, as well as correlations to laboratory capacities, were calculated using the Pearson's product-moment correlation coefficient or with the non-parametric Spearman's rank in cases where data were not normally distributed. Deviation from normally distributed data only occurred in the case of blood lactate concentration during submaximal testing of the three sub-techniques. In these cases, the Spearman's rank test was applied. The coefficient of variation (CV = standard deviation/mean) of time in different terrain sections of the XC skiing racecourse was calculated. Differences between prone and standing position with respect to shooting time and HR, as well as differences in pacing between laps, were tested using the paired sample *t*-test procedure. In addition, we performed two different stepwise multiple regression analyses, with model 1 having overall biathlon performance as dependent variable and XC skiing performance, shooting performance, shooting time, and range time as independent variables. In model 2, XC skiing performance was the dependent variable, and time in different terrains were independent variables. Alpha values of <0.05 determined the level of statistical significance and alpha values between 0.05 and 0.1 were considered trends. All statistical analyses were performed using IBM SPSS Software for Mac, Version 21.0 (SPSS Inc., Chicago, IL).

TABLE 2 | Overall performance, shooting performance, and time spent in the different components of a biathlon sprint competition among eleven elite male biathletes (mean ± SD).

Overall time (s)	1,574 ± 52		
XC skiing time (s)	1,355 ± 43		
Overall shooting component (s)	219 ± 23		
Terrain sections (s)	**Uphill**	**Varied**	**Downhill**
	701 ± 31	339 ± 11	315 ± 6
Shooting performance	**Prone**	**Standing**	**Total**
Hit rate (%)	91 ± 7	86 ± 6	89 ± 9
Penalty time (s)	34 ± 15	44 ± 15	78 ± 21
Shooting time (s)	31 ± 5	27 ± 4	58 ± 8
Range time (s)	41 ± 1	42 ± 1	83 ± 2

RESULTS

Overall Biathlon Sprint Race Performance

The distribution of XC skiing time, penalty time, shooting time, and range time in the overall biathlon sprint race time was 86.0, 5.0, 4.0, and 5.0%, respectively (**Table 2**). Stepwise multiple regression analysis demonstrated that XC skiing time explained

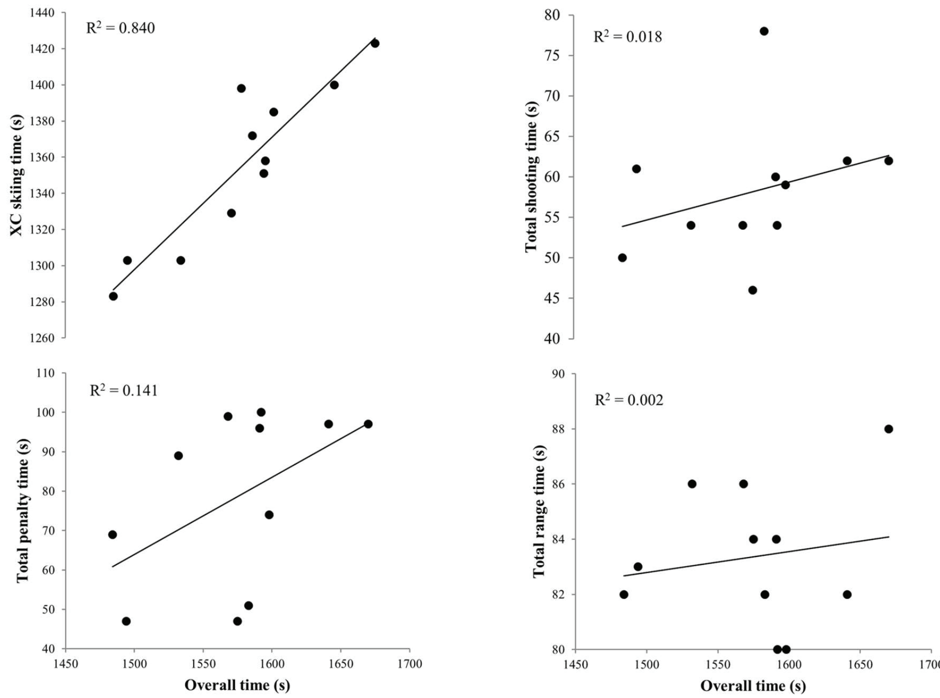

FIGURE 2 | Overall competition time in relationship to XC skiing time, penalty time, shooting time, and range time during a biathlon sprint competition among 11 elite male biathletes. Presented with individual data points and trend lines based on linear regression.

84.0% (semi-partial $R^2 = 0.603$), penalty time 14.2% (semi-partial $R^2 = 0.139$), shooting time 1.8% (semi-partial $R^2 = 0.020$), and range time 0.2% (semi-partial $R^2 = 0.002$) of overall sprint race time variance (all $p < 0.01$). In addition, XC skiing time was significantly correlated to overall biathlon sprint race performance ($r = 0.92$, $p < 0.01$; **Figure 2**).

XC Skiing Performance

Time, CVs of time and speed in different terrain sections of the XC skiing course are presented in **Table 3**. The distribution of total XC skiing time spent in uphill, varied, and downhill terrains were 52.0, 25.0, and 23.0%, respectively. Stepwise multiple regression analysis demonstrated that time in uphill explained 90.7% (semi-partial $R^2 = 0.315$), varied 8.6% (semi-partial $R^2 = 0.023$) and downhill terrain 0.7% (semi-partial $R^2 = 0.007$) of the total variation in overall XC skiing time (all $p < 0.01$). Time in uphill, varied, and downhill terrains were all significantly correlated to the overall XC skiing time ($r = 0.95$, 0.82, 0.72, respectively, all $p < 0.05$), and highest CVs of time were found in uphill terrain sections.

Shooting Performance

The average hit rate was 89 ± 9% with 91 ± 7% in the prone position, which was significantly better than the 86 ± 6% in the standing position ($p < 0.05$). On average, $\%HR_{max}$ was 87 ± 3% at the start of the shooting, both in the prone and standing position. During shooting, HR_{max} decreased to 69 ± 6% in the prone position, whereas this drop was significantly smaller, decreasing to 79 ± 4%, in the standing position (all $p < 0.01$). On average, the biathletes in this study shot 4 s (13%) faster in the standing than in prone position ($p < 0.05$). There was no significant relationship observed between the biathletes $\%HR_{max}$ at the start of shooting and shooting performance, in either prone or standing shooting.

Pacing Strategies and Skiing Speed Toward Shooting

Speed and HR profiles for the three laps are shown in **Figures 3**, **4**. Lap times (details provided in **Table 3**) on all three laps were significantly correlated to the overall XC skiing performance ($r = 0.84$, 0.95, 0.85, $p < 0.01$). The second and third laps were skied with 4.4 and 2.9% slower speeds in comparison to the first lap, respectively, with the last lap being significantly faster than the second lap (all $p < 0.05$). The participant's mean time in the defined section prior to shooting was 71 ± 2 and 73 ± 2 s for the prone and standing position, respectively. However, relative times in this section compared to total time in uphill and varied sections in the rest of the course on each lap were 0.7 ± 0.9%—points faster on the second and 3.1 ± 2.0%—points faster on the third lap compared to the first lap ($p < 0.05$). In addition, relative time in the section prior to shooting was inversely correlated to total time on lap 2 ($r = -0.64$, $p < 0.05$) and lap 3 ($r = -0.75$, $p < 0.01$) but not on lap 1 ($r = -0.49$, $p = 0.13$). There was no significant correlation observed between absolute or relative time or intensity in the last section before shooting and shooting performance (i.e., penalty time) in the prone or the standing position.

Laboratory Determinants of XC Skiing Performance

Results from laboratory testing is provided in **Table 4**. During submaximal roller skiing, RPE and $\%HR_{max}$ for G2 and G3 sub-techniques were significantly correlated (**Figure 5**, all $p < 0.05$), and tended to correlate for the G4 technique (both RPE and $\%HR_{max}$ $0.06 < p < 0.07$) with overall biathlon sprint race performance, XC skiing time and time spent in all terrains (**Table 5**). Furthermore, blood lactate concentrations in the G3 and G2 sub-techniques were significantly correlated to overall XC skiing time and time spent in downhill terrain sections (all $p < 0.05$) and showed a trend to time spent in uphill terrain ($p = 0.07$ and $p = 0.10$ for G2 and G3, respectively).

The observed correlations between submaximal roller skiing and XC skiing performance did not change when using measurements from roller skiing without the rifle, although carrying a rifle was associated with a 5% higher submaximal oxygen cost, 3% higher HR, ∼0.5 mmol/L higher blood lactate concentrations and 7% higher ratings of perceived exertion in comparison to skiing without a rifle (all $p < 0.01$). GE was unchanged, and the observed differences in GE between skiing with and without rifle were independent of sub-technique utilized at the different speeds and inclines (see details in **Table 4**).

TTE during maximal roller skiing correlated significantly with overall biathlon sprint race time, XC skiing time, as well as time spent in varied and downhill terrain (**Table 5**; all $p < 0.05$), whereas TTE tended to correlate with time in uphill terrain ($p = 0.07$). In addition, TTE did not correlate with XC skiing performance on the first or second lap but correlated strongly with the 3rd lap ($r = -0.84$, $p < 0.01$).

DISCUSSION

The primary aim of the present study was to investigate the contribution from XC skiing and shooting performance to the overall biathlon sprint performance, as well as the relationship to laboratory-measured capacities obtained during treadmill roller skiing. The main findings from the stepwise multiple regression analyses showed that XC skiing time explained 84% of the overall biathlon sprint performance, with shooting performance (i.e., penalty time) explaining 14% of the remaining variance and shooting time and range time together explaining the remaining 2%. Time spent in uphill terrain sections had the strongest impact on XC skiing performance (and explained 91% of the variance), although performance in all types of terrain showed significant associations. In addition, RPE and $\%HR_{max}$ during submaximal roller skiing as well as TTE during incremental treadmill roller skiing in the laboratory were significantly correlated to overall biathlon performance and isolated XC skiing performance.

Overall Biathlon Sprint Race Performance

In the current study, XC skiing performance was clearly the most important contributor to the overall biathlon sprint performance, which support previous studies on biathlon sprint races (Skattebo and Losnegard, 2017; Luchsinger et al., 2018). In our approach,

TABLE 3 | Length (for each 3-km lap), elevation, time and speed, as well as coefficient of variance (CV) of time within different sections of terrain during the three laps of the sprint competition among eleven elite male biathletes.

				Lap 1			Lap 2			Lap 3		
Section number	**Terrain type**	**Section length (m)**	**Elevation (m/%)**	**Mean section time (s)**	**Time CV (%)**	**Mean section speed (m/s)**	**Mean section time (s)**	**Time CV (%)**	**Mean section speed (m/s)**	**Mean section time (s)**	**Time CV (%)**	**Mean section speed (m/s)**
S1	Varied[a]	45	–	9 ± 1	5.3	4.8	13 ± 2	13.6	3.4	13 ± 2	12.8	3.5
S2	Downhill	128	14/11	14 ± 1	6.2	9.5	14 ± 1	5.6	9.2	15 ± 1	7.3	8.9
S3	Varied[a]	226	–	27 ± 1	3.3	8.3	29 ± 1	4.4	7.8	30 ± 1	4.4	7.7
S4	Uphill	125	11/9	22 ± 1	5.2	5.6	24 ± 1	4.6	5.2	23 ± 2	6.7	5.4
S5	Varied[a]	304	–	36 ± 2	4.4	8.4	38 ± 2	4.5	8.0	38 ± 2	6.0	8.1
S6	Uphill	279	18/7	55 ± 3	5.3	5.0	58 ± 3	5.6	4.8	57 ± 4	6.9	4.9
S7	Downhill	428	27/6	41 ± 1	3.1	10.4	42 ± 1	2.8	10.2	43 ± 1	3.0	10.0
S8	Uphill	183	14/7	32 ± 2	5.8	5.8	33 ± 3	7.5	5.5	33 ± 2	6.6	5.6
S9	Downhill	288	18/6	30 ± 1	4.2	9.6	30 ± 1	3.4	9.6	31 ± 1	4.0	9.4
S10	Uphill	363	31/9	85 ± 6	6.6	4.2	87 ± 6	6.7	4.2	84 ± 7	8.1	4.3
S11	Downhill	178	15/8	19 ± 1	2.8	9.6	19 ± 1	3.4	9.4	19 ± 1	4.0	9.4
S12	Uphill	179	14/18	36 ± 1	4.0	5.0	37 ± 1	4.2	4.9	34 ± 2	7.1	5.2
S13	Varied[a]	289	–	35 ± 1	1.8	8.3	36 ± 1	2.4	8.1	35 ± 1	3.4	8.3
Sum	Varied	864	–	107	3.7	7.5	116	6.2	6.8	116	6.7	6.9
Sum	Uphill	1,129	88	230	5.4	5.1	239	5.7	4.9	231	7.1	5.1
Sum	Downhill	1,022	74	104	4.1	9.8	105	3.8	9.6	108	4.6	9.4
Total		3,015	118[b]	441 ± 14	3.2	6.8	460 ± 16	3.5	6.5	454 ± 20	4.4	6.6

[a] *Elevation is not provided for varied terrain sections since these parts of the course consist of small uphills and downhills, as well as flat sections. For detailed specifications of varied terrain, see the Methods section and **Figure 1**.*

[b] *Total climb in one lap.*

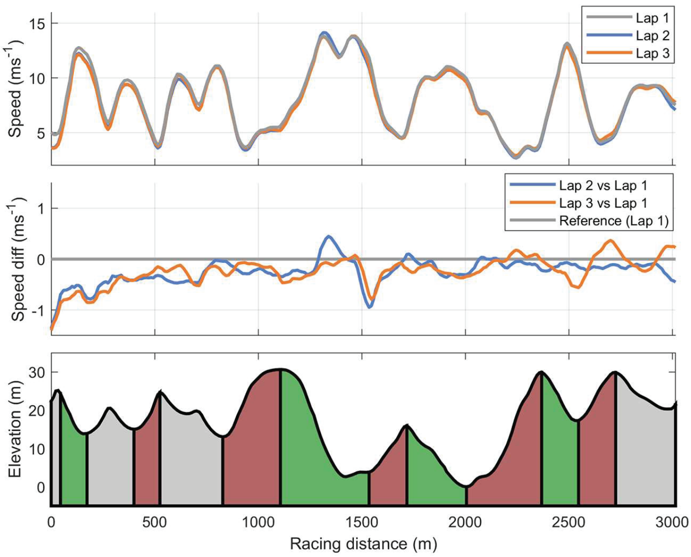

FIGURE 3 | Cross-country skiing speed for each of the three 3-km laps **(upper panel)** and speed differences on lap 2 and 3 compared to the first lap **(mid panel)** during a biathlon sprint competition among 11 elite male biathletes.

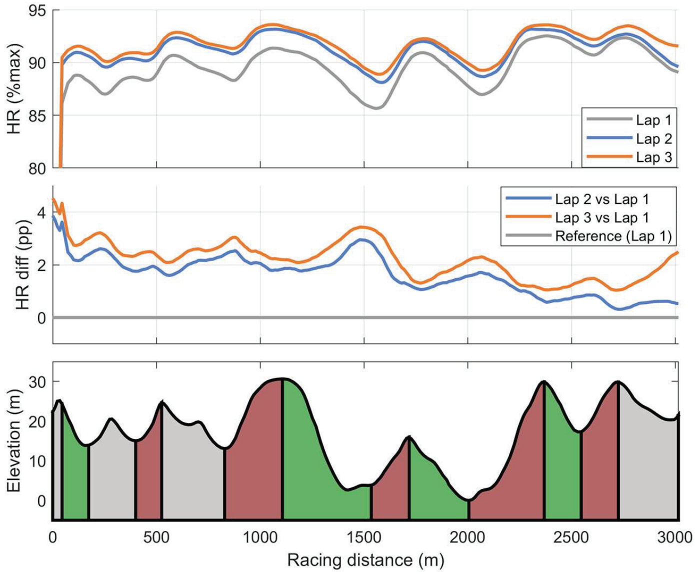

FIGURE 4 | Cross-country skiing heart rate (%HR_{max}) for each of the three 3-km laps **(upper panel)** and heart rate differences [in percent points (pp)] on lap 2 and 3 compared to first lap **(mid panel)** during a biathlon sprint competition among 11 elite male biathletes.

the stepwise multiple regression analysis demonstrated that XC skiing performance explained 84% of the variation in overall performance, while only 16% of the remaining variation in performance was explained by the overall shooting component (including shooting performance, shooting time, and range time). Furthermore, the correlation between XC skiing and overall performance was clearly larger than the corresponding correlations for the overall shooting component. These main findings extend upon the recent findings by Luchsinger et al. (2018) who revealed XC skiing time to be the most important contributor to the overall performance difference between top-10 results and those finishing among 21–30 in both sexes in biathlon World Cup sprint races. In the study by Luchsinger et al. (2018), XC time explained ~60% of the variance in overall performance when averaged over 47 World Cup sprint races. The larger influence of XC skiing time found here may be due to different methodologies between the studies, as well as natural variations across competitions (e.g., racecourses with different terrain in the sections prior to shooting and variation in snow and weather conditions). In our case, the shooting conditions were good (i.e., low wind speeds and good visibility) and athletes had relatively high hit rates, similar to the 92–93% hit rates reported among top-10 racers in World Cup sprint races (Luchsinger et al., 2018). Thus, these factors could additionally have contributed to the high impact of XC skiing performance on the overall biathlon sprint performance in the current study. However, the previous studies also highlight the larger importance of XC skiing performance than shooting performance to the overall biathlon sprint performance. Extending upon these findings, the current study provides detailed insight into the different components of the biathlon sprint competition, such as the importance of XC skiing in different terrains and the effects of pacing strategy.

XC Skiing Performance

The relative distribution of time spent in the uphill terrain sections accounted for 52% of the total XC skiing time and, additionally, time spent uphill revealed a near perfect correlation with XC skiing time. These findings are supported by higher CVs of time within the uphill compared to varied and downhill terrain sections, indicating greatest variation in time spent uphill, followed by time spent in the varied and downhill terrain sections, respectively. Altogether, the stepwise multiple regression analysis demonstrated that time in uphill explained ~91% of the variation in XC skiing performance. Indeed, uphill terrain as the most performance-differentiating part of the XC skiing performance is supported by previous research in XC skiing (Andersson et al., 2010; Bolger et al., 2015; Sandbakk et al., 2016b; Solli et al., 2018). However, in line with findings from XC skiing (Sandbakk et al., 2016b), performance in all types of terrain are important for achieving an excellent XC skiing performance in biathlon as shown by the significant correlations between all types of terrain and isolated skiing performance in this biathlon sprint race.

In line with findings from Biathlon World Cup sprint races (Luchsinger et al., 2018), the biathletes reduced their speed during the second and third lap compared to the first lap of the race, but skied the third lap faster compared to the second lap. This indicates that athletes maintain physical reserves to

TABLE 4 | Submaximal and maximal physiological responses and treadmill performance (mean ± SD) while roller skiing using different sub-techniques with (R) and without (N) the rifle on the back among eleven elite male biathletes.

Submaximal tests	G4R	G4N	G3R	G3N	G2R	G2N
VO_2 ($L \cdot min^{-1}$)	4.45 ± 0.28	4.24 ± 0.28**	4.44 ± 0.24	4.20 ± 0.23**	4.40 ± 0.26	4.20 ± 0.24**
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	57.9 ± 2.8	55.3 ± 2.6**	57.7 ± 2.0	54.6 ± 1.8**	57.3 ± 2.4	54.6 ± 2.4**
VO_2 in % VO_{2peak}	79 ± 5	75 ± 4**	78 ± 4	74 ± 4**	78 ± 4	74 ± 4**
RER	0.95 ± 0.02	0.94 ± 0.03	0.94 ± 0.03	0.93 ± 0.03*	0.93 ± 0.03	0.91 ± 0.03**
HR ($beats \cdot min^{-1}$)	176 ± 8	171 ± 7**	178 ± 8	174 ± 8**	178 ± 7	174 ± 7**
HR in %HR_{max}	89 ± 3	87 ± 2**	90 ± 3	88 ± 3**	90 ± 3	88 ± 3**
RPE (6–20)	14 ± 1	13 ± 1**	14 ± 1	13 ± 1**	15 ± 1	14 ± 1**
BLa ($mmol \cdot L^{-1}$)	3.8 ± 1.3	3.3 ± 1.0**	4.3 ± 1.9	3.7 ± 1.7**	4.3 ± 2.0	4.0 ± 1.8**
GE (%)	14.6 ± 0.7	14.6 ± 0.8	15.4 ± 0.5	15.6 ± 0.6	16.7 ± 0.7	16.7 ± 0.7
VO_{2peak}-test						
VO_{2peak} ($L \cdot min^{-1}$)				5.63 ± 0.41		
VO_{2peak} ($mL \cdot min^{-1} \cdot kg^{-1}$)				73.7 ± 3.9		
Peak RER				1.12 ± 0.30		
Peak HR ($beats \cdot min^{-1}$)				193 ± 8		
Peak BLa ($mmol \cdot L^{-1}$)				13.5 ± 1.3		
RPE (6-20)				19 ± 1		
TTE (s)				260 ± 20		

*VO_2, oxygen uptake; HR, heart rate; HR_{max}, maximal heart rate based on outdoor tests from the year prior to this study; RPE, rating of perceived exertion; BLa, blood lactate concentration; GE, gross efficiency; VO_{2peak}, peak oxygen uptake from incremental test to exhaustion; TTE, time to exhaustion; *Significant difference between with and without rifle within sub technique (**$p < 0.01$,*$p < 0.05$).*

increase speed during the latter part of the race. Specifically, the slightly reduced speed during the second lap prior to shooting in the standing position may be a strategy to minimize a possible negative effect of exercise intensity on shooting performance. This assumption is strengthened by findings in XC skiing where the athletes (who do not stop to shoot during the race) employ a more clear positive pacing strategy (although with a short end spurt) (Bolger et al., 2015; Losnegard et al., 2016; Sandbakk et al., 2016b). Extending upon the findings from World Cup sprint races, the detailed race analysis in this study shows that the time in the last section prior to shooting relative to the overall lap time was inversely correlated to total XC skiing time on lap 2 and 3. This means that faster skiers generally employed higher speed through the entire laps 2 and 3, but that they paced slower toward standing shooting compared to slower skiers. This pacing strategy fits well to the fact that biathletes miss more in the standing position than in prone. It also means that slower biathletes should carefully evaluate race tactics concerning the approach to the shooting range. A possible limitation of our approach is the use of a GPS watch with 1-Hz sampling frequency that has some accuracy limitations in comparison to high-end GNSS-systems (e.g., a 10 Hz standalone GNSS receiver or a differential GNSS; Gløersen et al., 2018). However, attaching standalone high-accuracy GNSS-units onto the biathletes was not an option in this case, as we have not been able to identify a mounting solution that the top elite biathletes find acceptable for high-level competitions. Also, a recent study (Gløersen et al., 2018) where the applied GPS watches were validated indicates sufficient accuracy for our approach. Still, future field-based studies in biathlon should aim to apply higher-accuracy GPS-systems in combination with more advanced sensor technology (e.g., accelerometers and gyroscopes) to gain further knowledge of the competitive demands in biathlon.

Shooting Performance

The biathletes in this study hit 91 ± 7 and 86 ± 6% of the targets in the prone and standing position, respectively, which is almost equal to the average shooting performance of Top-10 in the World Cup sprint races (Luchsinger et al., 2018). In line with these findings from the biathlon World Cup and Olympic Games, we found a ∼5% lower hit rate in the standing compared to the prone position, which was accompanied by a 23% longer penalty time. Thus, most biathletes lose more time due to missed targets in the standing position than in prone in the biathlon sprint competition.

The biathletes' skiing intensities found here are also in line with previous findings of biathlon competitions (Hoffman and Street, 1992). Thus, the biathletes approach the shooting range with similar physiological response as seen 25 years earlier. However, here we found a smaller decrease in %HR_{max} during shooting than reported by Hoffman and Street (1992), which is probably explained by shorter shooting times employed by the biathletes in our study compared to the group of biathletes studied by Hoffmann and Street in 1992. The greater reduction in HR in prone compared to standing position found in this study was also in agreement with Hoffman and Street (1992), which is likely explained by the 13% longer shooting time in prone position in combination with higher HR in upright compared to supine position. The reduction in HR during shooting also puts different demands to the different shots fired in a 5-shot-series and the high HR on the first shot

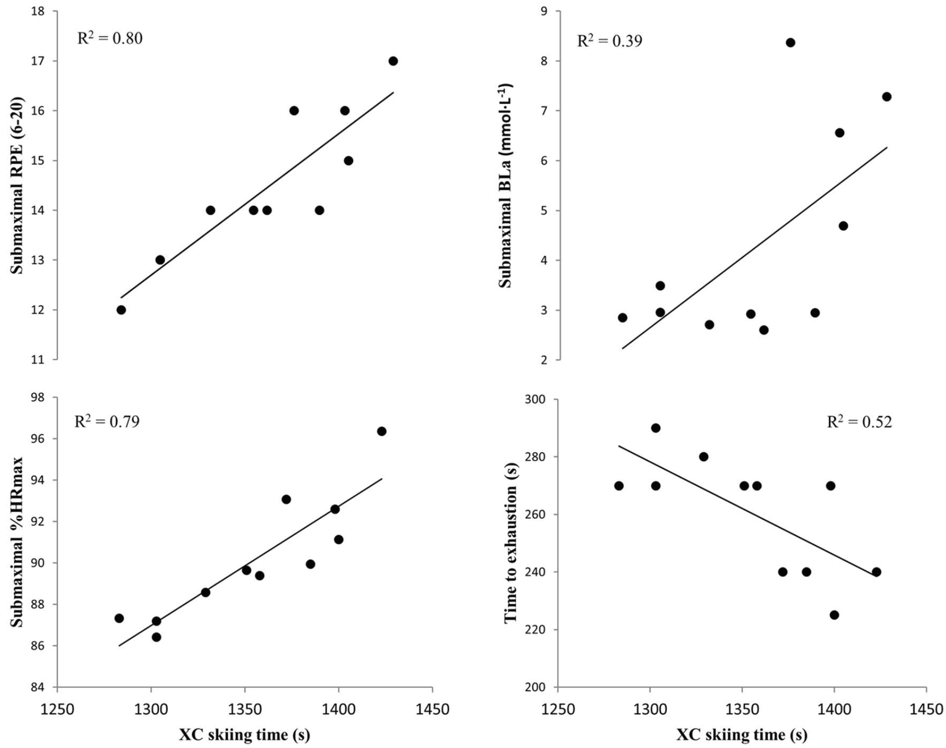

FIGURE 5 | Cross-country (XC) skiing time in relationship to rating of perceived exertion (RPE), relative heart rate (%HR_{max}), blood lactate concentrations (BLa) during submaximal roller skiing using the G2 sub-technique, and time to exhaustion during maximal roller skiing among 11 elite male biathletes. Presented with individual data points and trend lines based on linear regression.

could probably be one reason why biathletes miss the first shot twice as much as the second or third shot during prone shooting in biathlon World Cup sprint races (Luchsinger et al., 2018).

In another study, Hoffman et al. (1992) demonstrated that the exercise intensity negatively influenced parameters related to shooting technique in the standing position but to a lesser extent in prone position. Although no correlation between exercise intensity and shooting performance was seen for any of the shooting positions in our study, this might be explained by the relatively high hit rates and few mistakes to base the statistical tests on. In the future, more detailed analysis of the biathletes' hit points (i.e., measured as distance from center or group diameter) could probably provide additional information on the effect of exercise intensity and the risk of misses at the shooting range. Indeed, Hoffman et al. (1992) showed that hit rate was not affected by exercise intensity, whereas several detailed parameters related to shooting performance such as wobble diameter (movement of the rifle 1 s prior to trigger pull) and the spread of hits (mm) increased with higher exercise intensity, especially in the standing position. Thus, it might be that more detailed analysis of the spread of hits would reveal other relationships to exercise intensity than in our study. Interestingly, it has been suggested that the most important parameters of biathlon shooting technique are movement of the rifle in the vertical direction and cleanness of triggering (i.e., movement of the rifle 0.2–0.0 s before triggering; Ihalainen et al., 2018). This study additionally found that these parameters were negatively affected by high intensity exercise in both junior and elite biathletes, but that elite biathletes scored better than juniors on these technique parameters (Ihalainen et al., 2018). Altogether this indicates that biathletes' shooting technique is altered more by intense exercise than what can be seen on shooting performance measured as number of hits during a competition. This highlights the importance of combining laboratory designed studies with ecologically valid studies measuring actual biathlon race performance. Therefore, further research should examine the relationship between pacing toward shooting and detailed shooting performance (i.e., measure movement of the rifle, spread of hits) through designs that are more experimental in nature.

TABLE 5 | Correlations between physiological and performance variables obtained during submaximal and maximal roller skiing and the different XC skiing components among 11 elite male biathletes.

	Total time (s)	XC time (s)	Uphill terrain (s)	Varied terrain (s)	Downhill terrain (s)
Submaximal G4					
VO_2 ($L \cdot min^{-1}$)	−0.07	0.07	0.17	−0.27	0.17
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	0.05	0.16	0.16	−0.02	0.34
VO_2 in % VO_{2peak}	0.26	0.29	0.25	0.13	0.55
HR ($beats \cdot min^{-1}$)	0.28	0.07	−0.05	0.34	0.15
HR in % of HR_{max}	0.91**	0.89**	0.87**	0.71*	0.58
RPE (6-20)	0.81**	0.93**	0.95**	0.64*	0.57
BLa ($mmol \cdot L^{-1}$)	0.45	0.49	0.43	0.35	0.63*
GE (%)	−0.05	−0.11	−0.15	0.09	−0.19
Submaximal G3					
VO_2 ($L \cdot min^{-1}$)	−0.00	0.17	0.28	−0.21	0.12
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	0.18	0.30	0.34	0.11	0.33
VO_2 in % VO_{2peak}	0.40	0.43	0.39	0.26	0.58
HR ($beats \cdot min^{-1}$)	0.31	0.14	0.00	0.37	0.27
HR in % of HR_{max}	0.85**	0.89**	0.87**	0.67*	0.69*
RPE (6-20)[b]	0.76**	0.84**	0.82**	0.58*	0.71*
BLa ($mmol \cdot L^{-1}$)	0.51	0.61*	0.53	0.48	0.78**
GE (%)	−0.19	−0.31	−0.37	−0.07	−0.21
Submaximal G2					
VO_2 ($L \cdot min^{-1}$)	0.02	0.29	0.37	−0.07	0.28
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	0.19	0.46	0.44	0.26	0.54
VO_2 in % VO_{2peak}	0.39	0.53	0.47	0.36	0.72*
HR ($beats \cdot min^{-1}$)	0.27	0.13	−0.01	0.37	0.30
HR in % of HR_{max}	0.80**	0.89**	0.85**	0.67*	0.73*
RPE (6-20)	0.80**	0.90**	0.86**	0.70*	0.70*
BLa ($mmol \cdot L^{-1}$)	0.46	0.63*	0.56	0.46	0.75**
GE (%)	−0.21	−0.48	−0.50	−0.23	−0.44
Maximal roller skiing					
VO_{2peak} ($L \cdot min^{-1}$)	−0.25	−0.11	−0.01	−0.30	−0.16
VO_{2peak} ($mL \cdot min^{-1} \cdot kg^{-1}$)	−0.22	−0.16	−0.12	−0.14	−0.30
TTE (s)	−0.67*	−0.72*	−0.56	−0.75**	−0.85**

*VO_2, oxygen uptake; HR, heart rate; HR_{max}, maximal heart rate based on outdoor tests from the year prior to this study; RPE, rating of perceived exertion; BLa, blood lactate concentration; GE, gross efficiency; VO_{2peak}, peak oxygen uptake from incremental test to exhaustion; TTE, time to exhaustion. *$p < 0.05$, **$p < 0.01$.*

Laboratory Determinants Associated With XC Skiing Performance

The predictive values of RPE and $\%HR_{max}$ during submaximal roller skiing for XC skiing time and time spent in different terrains were significant for all three sub-techniques. In addition, lower blood lactate concentrations in the G3 and G2 sub-techniques were positively correlated to better XC skiing performance and time spent in downhill terrain. Together, this indicates that the submaximal stages were less demanding for the best performing biathletes in the competition. These findings are in line with a study in cycling, indicating that submaximal measurements based on RPE revealed best relationships both with performance and changes in performance over time (Rodriguez-Marroyo et al., 2017). This highlights the relevance of simply measured variables, such as RPE and $\%HR_{max}$, to predict biathlon sprint race performance.

Blood lactate levels on the submaximal stages (performed in uphill terrain) were only correlated to downhill competition performance and not to uphill or varied terrain. This could be explained by the fact that athletes who are faster in the uphill sections are also able to maintain speed better in this terrain and thereby ski faster over hilltops, which subsequently provides higher speeds in the downhill sections. This theory is supported by findings in XC skiing, revealing higher variations in speed at the end of uphill sections and subsequent transition into downhill sections (Andersson et al., 2010), indicating the importance of skiing fast over hilltops in order to create speed in downhills. In addition, a recent study of XC skiers indicate a lag in the physiological response after hilltops and strengthens the importance of being able to create speed at the top of each downhill section (Haugnes et al., 2019).The stronger association between XC skiing performance and RPE or $\%HR_{max}$ than the corresponding relationship with blood lactate concentration can likely be explained by the different physiological behavior of these variables; blood lactate concentration might be relatively similar between athletes of different performance levels at low submaximal speed (such as the aerobic steady-state conditions used here), whereas RPE and $\%HR_{max}$ would increase more linearly with increased individual load—and thereby be higher in lower level athletes at the same speed.

The submaximal oxygen cost and GE did not correlate to XC skiing performance in this biathlon sprint competition, which is in contrast to studies in the skating technique in XC skiing (Sandbakk et al., 2010, 2011b, 2013). This means that faster biathletes, who are able to ski on a lower $\%HR_{max}$ and RPE on the submaximal stages, are not more efficient than lower level biathletes, indicating that additional factors than efficiency would explain the differences in XC skiing performance levels. The most likely explanatory factor is that better XC skiers with similar efficiencies have higher "maximal capacities," which was also indicated here by the longer TTE of faster skiers. However, VO_{2peak} did not correlate with XC skiing performance in this study, and other factors than measured in our design must have contributed to explain the performance differences in XC skiing both on the field and during the treadmill test. This could be factors such as indices of the anaerobic threshold (which subsequently would allow skiers to compete on a higher fraction of their "maximal capacity") or anaerobic energy delivery capacity. Therefore, a possible limitation of our approach is the lack of additional physiological measurements (e.g., lactate threshold). The fact that biathletes stop during shooting and have shorter loops of skiing than normally employed in cross-country skiing could imply that biathletes to a greater extent than cross-country skiers must be able to accelerate from more stops during a race and create faster speeds through more turns and smaller but more uphills. However, analyses of the differences between course profiles in XC skiing and biathlon are lacking so the latter assumption remains unknown.

The submaximal stages using different sub-techniques were performed both with and without carrying a rifle, but the order of the stages was not randomized since our purpose was to correlate physiological and perceptual responses with race performance and not to examine the effects of carrying a rifle *per se*. However, the observed correlations did not change when using measurements without carrying a rifle, despite the associated increase in submaximal oxygen cost, HR and blood lactate concentrations compared to roller skiing without the rifle. This indicates relatively robust results in these cases.

Performance in the laboratory, measured as TTE, correlated to overall biathlon sprint race performance, XC skiing time on the last lap and time spent in varied and downhill terrains. When correlated separately with performance on each lap, TTE correlated strongly with performance on the last lap, but not with the first or the second lap. This indicates that better performing athletes in the laboratory adjust their pacing on the two first laps before shooting, which is different from XC skiing, where skiers generally use a more positive pacing than in biathlon. TTE during treadmill roller skiing has also been shown to correlate with on-snow performance in elite XC skiers (Sandbakk et al., 2011a). Hence, this emphasizes the relevance of determining performance by an incremental test to exhaustion in the laboratory when monitoring the development of biathletes' performance level. In addition, it indicates that better performing athletes use different pacing strategies than their lower level peers.

In the current study, no significant associations were identified between VO_{2peak} and XC skiing time, nor time spent in different terrains. These findings are in agreement with Rundell and Bacharach (1995), who showed that TTE during treadmill running and performance during a 1 km double-poling time-trial on snow correlated significantly with performance during a biathlon sprint race among men, whereas VO_{2peak} did not. In contrast, previous observations in XC skiing highlight VO_{2peak} as a key determinant of performance (Sandbakk and Holmberg, 2017). The reason for these somewhat conflicting findings are not known but could be explained by differences in the heterogeneity of groups in the different studies or different demands in XC skiing compared to biathlon. However, the average VO_{2peak} among the participants in our study is lower than was previously found in Olympic- or World Championship medalists in biathlon (Tønnessen et al., 2015). In addition, the stages of rifle shooting, leading to periods of ∼60–90 s with a reduction in exercise intensity toward shooting in addition to the time spent at the shooting range make biathlon competitions even more interval-based than in XC skiing and pacing strategies may play a more important role.

CONCLUSION

The present study showed that XC skiing performance provides greatest impact on overall biathlon sprint performance, with 84% of the variance being explained by this component and most of the variance determined by the time spent in the uphill terrain sections. Overall, this indicates that biathletes should emphasize the development of their XC skiing performance to perform well in biathlon sprint competitions. Although biathletes need to ski fast in all types of terrain, improvements in uphill-specific performance seem to have a particular impact on the overall performance in the biathlon sprint competition. While shooting performance in general is an important component in biathlon, it had clearly lower importance than XC skiing in this study, where penalty time explained 14% of the remaining variance in overall sprint race performance and shooting time and range time together only 2% of the final variance. In addition, race tactics and pacing are important aspects in biathlon competitions and our data indicate a further potential to enhance performance by optimizing pacing strategies, especially among the slower skiers who lose most time on the last lap to the faster skiers.

Based on treadmill roller ski tests in the laboratory, lower ratings of RPE and $\%HR_{max}$ during submaximal roller skiing in the three main sub-techniques of skating, as well as longer TTE during an incremental test to exhaustion, were strongly correlated to overall biathlon sprint performance and XC skiing time. Such laboratory-derived measures may therefore be validly used to distinguish biathletes of different performance levels and to track progress of their XC skiing capacity. In contrast, the non-significant relationships to peak oxygen uptake and gross efficiency indicate that other variables than those measured here (such as anaerobic capacity) also contributed to TTE and biathlon performance in these athletes.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

All authors contributed in the design of the study. HL and RT collected the data. JK performed the data handling of GPS and HR-signals. RT performed the statistical analyses. All authors contributed to the writing of the manuscript and to the design of figures and tables.

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