Physiological and biomechanical aspects of rifle carriage during biathlon skiing

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To my two A's, the best I have

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Abstract

Biathlon is an endurance-based winter sport that combines cross-country (XC) skiing with rifle marksmanship. While skiing, biathletes carry the rifle (weighing ≥ 3.5 kg) on their backs. However, research regarding the effects of rifle carriage in biathlon is lacking. Therefore, the aim of this body of work was to investigate how rifle carriage in biathlon affects physiological and biomechanical variables related to biathlon skiing performance, and possible sex differences associated with rifle carriage. Physiological (*Study I*) and kinematical *(Study III*) effects of rifle carriage were tested in a laboratory using treadmill roller-skiing, whereas the effects of rifle carriage on gear distribution were tested in the field on snow (*Study IV*). In addition, the effects of supplementary rifle-carriage training on physiological variables and skiing performance were investigated (*Study II*).

The results of this thesis show that rifle carriage affects both physiological and biomechanical variables during biathlon skiing. From a physiological perspective, skiing with the rifle (WR) increased respiratory variables (oxygen uptake, ventilation rate and carbon dioxide production) and blood lactate concentration (BLa) at workloads around or above the lactate threshold during submaximal skiing, while the speed at 4 mmol of BLa ($speed_{@4mmol}$) decreased compared to skiing without the rifle (NR) (*Study I*). During maximal treadmill roller-skiing the anaerobic metabolic rate (MR_{an}) decreased when skiing WR, and MR_{an} together with $speed_{@4mmol}$ explained ~ 80% of the variation in time trial (TT) performance WR (*Study I*). Rifle carriage also impaired TT performance during both treadmill roller-skiing in the laboratory (*Study I*) and on-snow skiing in the field (*Study IV*). From a biomechanical perspective, skiing WR decreased flexion/extension range of motion (ROM) in the shoulder and thorax,

while abduction/adduction and internal/external rotation ROM in the shoulder and thorax increased compared to NR (*Study III*). Rifle carriage also decreased the maximal height of the shoulders during skiing (i.e., exhibiting a lower body position), which was related to a more forward tilt of the thorax compared to skiing NR (*Study III*). During the on-snow TT, skiing WR increased the use of gear 2, while the distance and time spent in gear 3 was decreased (*Study IV*). Although the relative mass of the rifle was greater for the women compared to the men (*Study I–IV*), the physiological, performance and biomechanical responses to rifle carriage were similar for both sexes. The only exception was a larger decrease in flexion/extension ROM in the thorax during skiing WR for the women compared to the men (*Study III*). During the training intervention, only ~ 10% of the endurance-based training was performed WR for the control group. Compared to the control group, one additional training session per week (~ 2 h·week^{-1}) WR over a 16-week period did not affect physiological variables or improve roller-skiing performance (*Study II*).

This body of work showed that rifle carriage affects physiological, biomechanical and performance aspects of biathlon skiing, and that a relatively low amount of the training is performed WR. This thesis contributes new knowledge of the unique demands of biathlon skiing, which can inform development of sport-specific training. To improve biathlon skiing performance, training WR may be individualized to each athlete, with specific focus on training intensities and technique development when skiing with the rifle.

Keywords: 3D-measurement, anaerobic energy contribution, cross-country skiing, kinematics, lactate threshold, load carriage, oxygen uptake, performance, sex differences, sub-techniques, training

Summary in Swedish

Skidskytte är en uthållighetsbaserad vinteridrott som kombinerar längdskidåkning med gevärsskytte. Under skidåkningsmomentet bär skidskytten sitt gevär (vikt ≥ 3.5 kg) på ryggen. Forskningen om hur geväret påverkar skidåkningen inom skidskytte är dock begränsad. Syftet med denna avhandling var därför att undersöka hur bärandet av geväret inom skidskytte påverkar fysiologiska och biomekaniska variabler relaterade till skidprestation, och eventuella könsskillnader associerade med bärandet av geväret. Fysiologiska *(Studie I)* och kinematiska *(Studie III)* effekter av bärandet av geväret undersöktes genom rullskidåkning på rullband i laboratoriemiljö, medan gevärets påverkan på växelval undersöktes i fält genom skidåkning på snö *(Studie IV).* Dessutom undersöktes hur en ökad mängd träning med geväret påverkar fysiologiska variabler och skidprestation *(Studie II).*

Avhandlingens resultat visade att bärandet av geväret under skidåkningsmomentet i skidskytte påverkar både fysiologiska och biomekaniska variabler. Från ett fysiologiskt perspektiv, så ökar skidåkning med gevär (WR) respiratoriska variabler (syreupptag, ventilation och koldioxidproduktion) och koncentrationen av blodlaktat (BLa) vid intensiteter nära eller över laktattröskeln vid submaximal skidåkning, medan hastigheten vid 4 mmol av BLa ($speed_{@4mmol}$) minskade i jämförelse med utan gevär (NR) *(Studie I)*. Vid maximal rullskidåkning på rullband WR minskade den anaeroba energiomsättning, vilken tillsammans med $speed_{@4mmol}$ förklarade ~ 80% av variationen i prestation för tidsloppet (TT) vid skidåkning WR (*Studie I*). Bärandet av geväret försämrade också TT prestationen både för rullskidåkning på rullband (*Studie I*) och för skidåkning på snö i fält (*Studie IV*). Från ett biomekaniskt perspektiv så minskade skidåkning WR rörelseomfånget (ROM) för flexion/extension i axel

och torso, medan ROM för abduktion/adduktion och intern/extern rotation i axel och torso ökade i jämförelse med NR (*Studie III*). Bärandet av geväret minskade också den maximala höjden av axlarna under skidåkning (dvs. uppvisade en lägre kroppsposition), vilket var relaterat till en större framåtlutning av torson i jämförelse med NR (*Studie III*). För det TT som genomfördes på snö, så ökade skidåkning WR användandet av växel 2, medan distans och tid i växel 3 minskade (*Studie IV*). Även fast gevärets vikt i förhållande till kroppsvikt var högre för kvinnor än för män (*Studie I–IV*), så var den fysiologiska, prestationen och biomekaniska responsen till bärandet av geväret liknande för båda könen. Det enda undantaget var en större minskning i ROM för flexion/extension i torson för kvinnor jämfört med män vid skidåkning WR (*Studie III*). Under träningsinterventionen genomfördes endast ~ 10% av uthållighetsträningen WR för kontrollgruppen. I jämförelse med kontrollgruppen, så hade ett extra träningspass per vecka WR (~ 2 timmar·vecka^{-1}) under en 16 veckors period ingen effekt på fysiologiska variabler eller förbättrade skidprestationen (*Studie II*).

Denna avhandling visade att bärandet av geväret påverkar fysiologiska, biomekaniska och prestationsaspekter vid skidåkning, samt att en relativt liten mängd av träningen genomförs WR. Denna avhandling ökar vår kunskap om de unika krav som skidåkningsmomentet i skidskytte ställer, vilket kan vara viktigt för utvecklingen av den idrottsspecifika träningen. För att förbättra skidprestationen inom skidskytte bör träningen WR vara individuellt anpassad till varje atlet, med specifikt fokus på träningsintensitet och teknikutveckling vid skidåkning med gevär.

List of papers

This thesis is based on the following four papers, herein referred to by their Roman numerals:

Study I JONSSON KÅRSTRÖM, M., MCGAWLEY, K. & LAAKSONEN, M. S. (2019). Physiological Responses to Rifle Carriage During Roller-Skiing in Elite Biathletes. *Frontiers in Physiology, 10,* 1519. doi: 10.3389/fphys.2019.01519

Study II JONSSON KÅRSTRÖM, M., MCGAWLEY, K. & LAAKSONEN, M. S. (2021). Effects of Additional Rifle-Carriage Training on Physiological Markers and Roller-Skiing Performance in Well-Trained Biathletes. *Journal of Science in Sport and Exercise, 3,* 292-302. doi: 10.1007/s42978-021-00107-3

Study III JONSSON KÅRSTRÖM, M., STÖGGL, T., LUND OHLSSON, M., MCGAWLEY, K. & LAAKSONEN, M. S. (2022). Kinematical Effects of Rifle Carriage on Roller Skiing in Well-Trained Female and Male Biathletes. *Scandinavian Journal of Medicine and Science in Sports, 00,* 1-11. doi: 10.1111/sms.14276

Study IV JONSSON KÅRSTRÖM, M., STAUNTON, C., MCGAWLEY, K., BJÖRKLUND, G., & LAAKSONEN, M. S. (2022). The Effect of Rifle Carriage on Gear Distribution During On-Snow Biathlon Skiing. *In Review (Journal of Sport Sciences)*

Abbreviations

η^2_p	Partial Eta square
$\sum O_2$ deficit	Accumulated oxygen deficit
3D	Three-dimensional
ANOVA	Analysis of variance
BLa	Blood lactate concentration
BLa_{max}	Maximal blood lactate concentration
CG	Control group
CL	Cycle length
COM	Centre of mass
CR	Cycle rate
CT	Cycle time
E_{gross}	Gross energy expenditure
EMG	Electromyography
GE	Gross efficiency
GNSS	Global navigation satellite system
HR	Heart rate
HR_{max}	Maximal heart rate
HR_{mean}	Mean heart rate
IBU	International Biathlon Union
IG	Intervention group
IMU	Inertial measurements unit
IQR	Interquartile range
LT	Lactate threshold
M_{tot}	Total mass
MAOD	Maximal accumulated oxygen deficit
MOD_{up}	Moderate uphill
MR_{ae}	Aerobic metabolic rate
MR_{an}	Anaerobic metabolic rate

MR_{demand}	Total metabolic demand
NP	Skiing without pole propulsion, no poles
NR	Without rifle
O_2	Oxygen
OBLA	Onset of blood lactate accumulation
PO	Power output
PP	Pole plant
RER	Respiratory equivalent ratio
RER_{max}	Maximal respiratory exchange ratio
ROM	Range of motion
RPE	Rating of perceived exertion
SD	Standard deviation
$Speed_{@4mmol}$	Speed at 4 mmol·L^{-1} of BLa
$STEEP_{up}$	Steep uphill
TT	Time trial
$Vert_{dist}$	Vertical distance between shoulder and treadmill
$\dot{V}_E$	Ventilation rate
$\dot{V}_{Emax}$	Maximal ventilation rate
$\dot{V}CO_2$	Carbon dioxide production
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2mean}$	Mean oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake
WR	With rifle
XC skiing	Cross-country skiing

1 Introduction

1.1 The history of biathlon

Biathlon is a winter sport that combines cross-country (XC) skiing with rifle marksmanship. The sport has its roots in the military setting and the first "biathlon" competition is believed to have been held in 1767, where Norwegian soldiers competed in shooting, XC skiing and downhill skiing. Biathlon was included in the Winter Olympics in 1924, 1928, 1936 and 1948, but only as a "show sport". Modern biathlon competitions evolved in the late 1950s, with the first World Championships held in 1958 and the first Winter Olympic medals awarded in 1960 (IBU, 2022a) (Figure 1). In the early to mid-20th century, high-power cartridges were used for shooting and the distance between the shooting range and targets varied between 100 and 250 m. In 1978, the rifle type was standardized (small-bore rifles with 0.22-inch ammunition) and the shooting distance was set at 50 m. In 1980, paper targets were replaced with metal targets, which allowed spectators to see the results immediately. From this point the popularity of the sport started to increase, with higher numbers of athletes, competing nations, spectators and sponsors, as well as the inclusion of female competitors and new competition formats (Figure 1). During the winter of 2021/2022 an average of 878 000 viewers watched the World Cup competitions in Sweden (SVT, 2022) and the 2021 World Championships in Pokljuka, Slovenia were broadcasted in more than 50 countries, with 160 million hours of biathlon viewed worldwide (IBU, 2021).

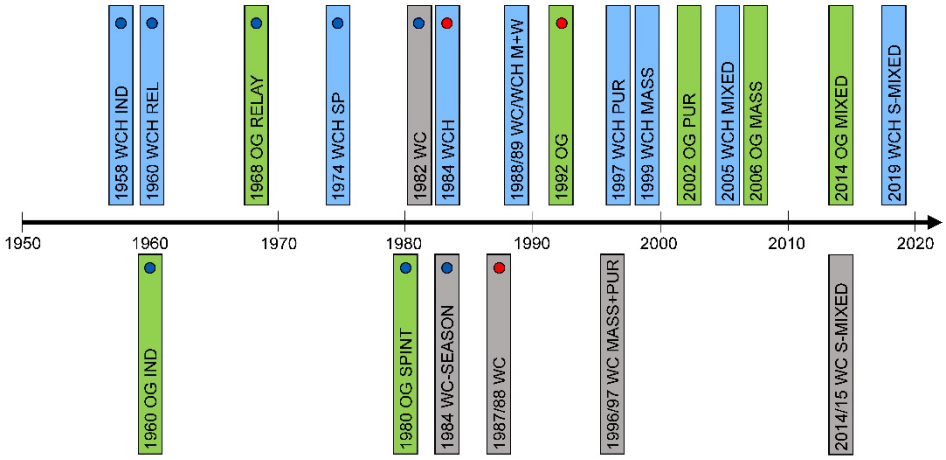

Figure 1. The timeline for first appearance of the different competition formats for men and women in the sport of biathlon. Blue bars symbolize World Championship events (WCH), green bars Winter Olympic Games events (OG) and grey bars World Cup events (WC). The blue dots symbolize the milestones for the men only and the red dots symbolize the milestones for the women only.
IND = individual; REL = relay; SP = sprint; MASS = mass-start; PUR = pursuit; MIXED = mixed relay; S-MIXED = single mixed relay; M = men; W = women.

In the research database PubMed, a search for *´biathlon´* (in the title, keywords and/or abstract) shows that the first publication was in 1986 and until the year 2000, only 15 articles had been published (Figure 2). The publications in biathlon have increased markedly during the last 22 years and until October 2022, 131 articles had been published. In these publications, many aspects of biathlon are covered, such as the skiing (physiology and biomechanics), performance analysis, shooting, waxing, medical and psychological aspects. In comparison, the number of published articles in XC skiing is higher (search word *´cross country skiing´* in the title, keywords and/or abstract), with 274 publications until 2000 and 916 publications until October 2022 (Figure 2). Publications regarding rifle shooting (search word *´rifle shooting´* in the title, keywords

and/or abstract) show similar numbers to those in XC skiing (Figure 2).

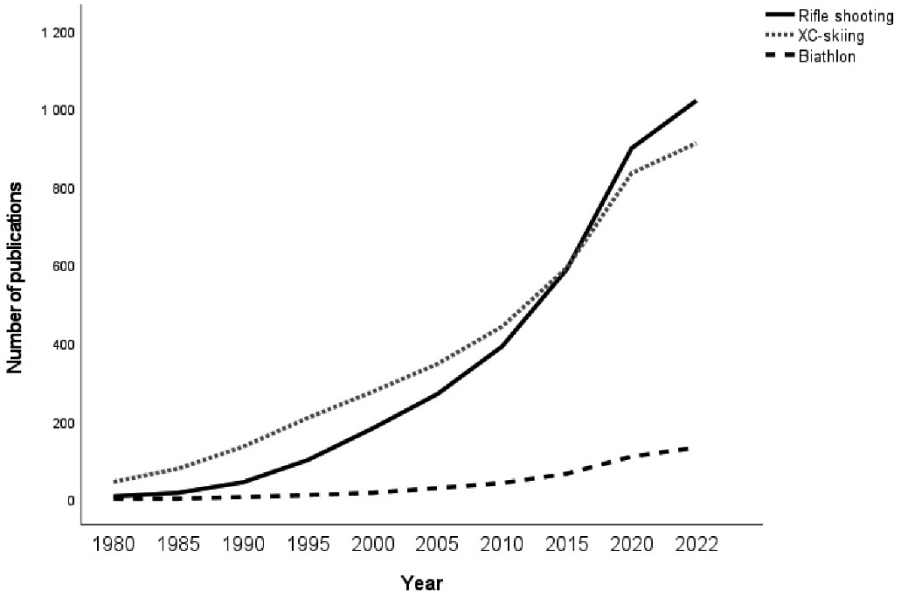

Figure 2. The number of publications from 1980 until October 2022 when searching for ´biathlon´ (dotted black line), ´cross-country skiing´ (dotted dark grey line) and ´rifle shooting´ (solid black line) in the title, keywords and/or abstract in the research database PubMed.

Because biathlon involves XC skiing, some of the research is transferable between sports; however, there are some differences in demands between biathlon and XC skiing. Firstly, biathlon involves 3 or 5 laps of skiing separated by 2 or 4 shooting bouts, thereby characterizing biathlon skiing as a more intermittent sport compared to XC skiing. Secondly, biathletes carry their rifle, weighing a minimum of 3.5 kg, on their back during skiing. Finally, the shooting is performed under time pressure during the recovery from high-intensity exercise, which impacts the pacing of the skiing. Nevertheless, the limited research in biathlon and the similarities

between biathlon and XC skiing (e.g., use of the same skating skiing technique and its associated sub-techniques), research from XC skiing plays an important role also for biathlon.

1.2 Competition formats

The biathlon World Cup season consists of ~ 22 individual competitions and ~ 6 relays for each sex, in addition to the World Championships or Olympic Games (IBU, 2022a). As such, a single biathlete can theoretically participate in ~ 35 competitions at the highest international level during each season. There are four individual competition formats (sprint, individual, pursuit and mass-start), with various types of starts, skiing distances, number of skiing laps, number and order of shooting bouts and types of penalty (Table 1). There are three types of relays (relay, mixed and single mixed relay), with various combinations of number and sex of the athletes in the teams (Table 1).

1.3 Biathlon performance

1.3.1 Development during the 2000s

Skiing speed accounts for ~ 45–65% of the variation in overall biathlon performance, depending on competition format and sex (Björklund et al., 2021; Björklund & Laaksonen, 2022; Dzhilkibaeva et al., 2019; Luchsinger et al., 2018; Luchsinger et al., 2019a; Luchsinger et al., 2020). Biathlon competitors' skiing speeds have increased in all individual competition formats during the 2000s (Björklund et al., 2021; Björklund & Laaksonen, 2022) and the development in skiing speed in the World Cup from season 2001/2002 until 2021/2022 is shown in Figure 3. The increased skiing speed is probably due to improvements in equipment, waxing, course preparations and changes in training regimens (Laaksonen et al., 2018a).

Table 1. Description of the different competition formats in biathlon (individual and relays). In the relays, each biathlete also has three spare shots per shooting bout, in the case of missed targets (IBU, 2022b).

	Start type	Competition time (mm:ss)	Skiing distance (km) (W / M)	Shooting positions	Type of penalty	Specific penalty
Sprint	Single-start	20:00–25:00	7.5 / 10	P-S	Penalty loop	150 m
Individual	Single-start	45:00–50:00	15 / 20	P-S-P-S	Time	1 min
Pursuit	As results from sprint	30:00–35:00	10 / 12.5	P-P-S-S	Penalty loop	150 m
Mass-start	Mass start	35:00–40.00	12.5 / 15	P-P-S-S	Penalty loop	150 m
Relay (4 W *or* 4 M)	Mass start	70:00–75:00	4 * 6 / 4 * 7.5	4 * P-S	Penalty loop	150 m
Mixed relay (2 W + 2 M)	Mass start	70:00–80:00	4 * 6 *or* 4 * 7.5	4 * P-S	Penalty loop	150 m
Single mixed relay (1 W + 1 M)	Mass start	35:00–40:00	(2 * 3) + (3 + 4.5)	2 * (2 * P-S)	Penalty loop	75 m

W = women; M = men; P = prone; S = standing

In both single mixed and mixed relays, the start order (women/men) is alternated according to the competition program decided by the International Biathlon Union (IBU).

Mixed relay - the longer skiing distance is used when the men start and the shorter distance is used when the women start.

Single-mixed relay - the fourth leg consists of an extra skiing lap (into the finish) and therefore the skiing distance is longer than for the other legs.

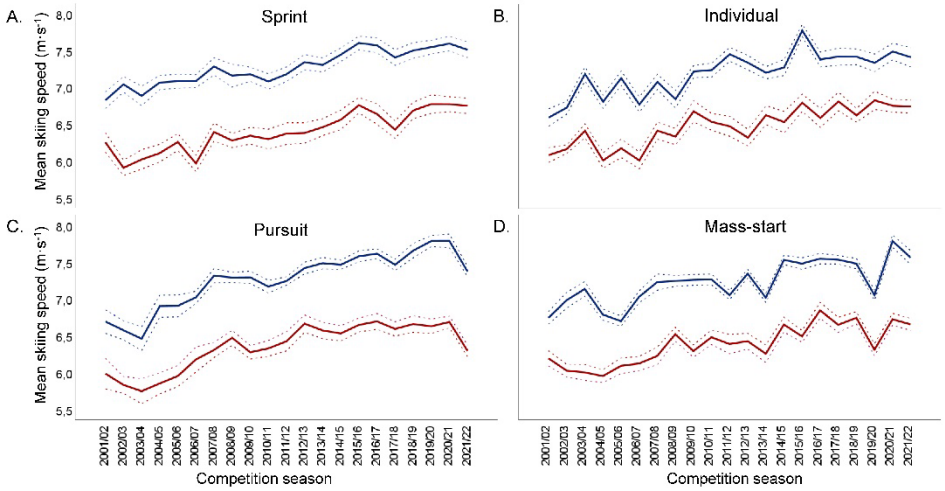

Figure 3. Development in skiing speeds in the World Cup from season 2001/2002 until 2021/2022 for the sprint (A), individual (B), pursuit (C) and mass-start (D) competitions. Data is presented as mean (solid lines) and standard deviation (dotted lines) for biathletes placed in the top ten from each competition for women (red lines) and men (blue lines). The figures are adapted from Björklund et al. (2021) and Björklund and Laaksonen (2022).

From the season 2002/2003 to 2018/2019, skiing speed in biathlon sprint competitions increased by ~ 13% and 7% for women and men, respectively (Björklund & Laaksonen, 2022). The same trend was found for the individual competition format, with an ~ 9% and 13% increase in skiing speed for women and men, respectively (Björklund & Laaksonen, 2022). During the same period, skiing speed also increased for female and male biathletes in both the pursuit (by ~ 14% and 16%, respectively) and mass-start competitions (by ~ 12% and 7%, respectively) (Björklund et al., 2021). For the head-to-head competitions (i.e., pursuit and mass-start), the difference in skiing speeds between the biathletes placed in the top three and those placed 11–20 decreased from the season 2002/2003 to 2018/2019 (Björklund et al., 2021). This pattern was not evident for the

competition formats with an individual start (i.e., sprint and individual) (Björklund & Laaksonen, 2022), which might partly be explained by the effect of drafting when skiing together in a group and/or pacing pattern during the head-to-head competitions. Variations in skiing speeds between seasons can be affected by changes in weather conditions, competition venues for the different competition formats and/or race tactics. The largest variations are seen in the individual and mass-start competitions, where only 2–5 competitions are performed per season for each format, compared to 8–10 competitions for the sprint and pursuit formats.

Between the seasons of 2002/2003 and 2018/2019 the development in shooting performance in the World Cup has been negligible (Björklund et al., 2021; Björklund & Laaksonen, 2022). Shooting accuracy has not changed significantly during these years in any of the individual competition formats (Björklund et al., 2021; Björklund & Laaksonen, 2022), while the time spent at the shooting range decreased slightly between 2012 and 2019 in the pursuit and mass-start competitions (Björklund et al., 2021), but not in the sprint or individual events (Björklund & Laaksonen, 2022).

1.3.2 Performance in modern-day biathlon

Performance in biathlon is determined by skiing speed, shooting accuracy and shooting speed (Laaksonen et al., 2018a) and for all competition formats, skiing speed and shooting accuracy have the largest overall impact on performance, while shooting speed is less important (Björklund et al., 2021; Björklund & Laaksonen, 2022; Dzhilkibaeva et al., 2019; Luchsinger et al., 2018; Luchsinger et al., 2019a; Luchsinger et al., 2020). However, shooting speed may have a decisive role in competitions where final time differences are small between biathletes or during head-to-head situations, e.g., during the

final shooting bout during pursuits, mass-starts or relays (Björklund et al., 2021). In the World Cup, performance in the individual competition format are equally dependent on skiing speed and shooting accuracy (Luchsinger et al., 2019a), while in sprint competitions, skiing speed accounts for 59–65% of the variation in overall performance (Dzhilkibaeva et al., 2019; Luchsinger et al., 2018), with the skiing speed during the last lap having the largest impact on performance (Björklund & Laaksonen, 2022). Also, shooting accuracy relates to sprint performance (Björklund & Laaksonen, 2022) and explains 35% and 31% of the differences between positions 1–10 and 21–30 for men and women, respectively (Luchsinger et al., 2018). These findings highlight the importance of high skiing speeds as a determinant of biathlon performance, especially for the sprints, which is the competition format most commonly performed during a competition season (~ 10 sprints·year^{-1}).

In World Cup pursuits, biathletes start according to the results from the previous sprint competition and start time together with shooting accuracy explain ~ 80% (50% and 30%, respectively) of the variation in performance (Luchsinger et al., 2020). In the mass-start competitions, the major determining factor for final rank is shooting accuracy, followed by skiing speed (Björklund et al., 2021). The most frequent shooting result for the top three biathletes in the World Cup pursuit and mass-start competitions during the season 2002/2003 until 2018/2019 was one miss (out of 20 shots), which corresponds to one miss less than the biathletes placed 4–20 (Björklund et al., 2021). The biathletes placed on the podium also had a faster skiing speed compared to those placed 4–20 during pursuit and mass-start competitions (Björklund et al., 2021).

1.4 Physiological determinants of biathlon skiing performance

In biathlon, the total competition time for a single biathlete is 20–50 min, depending on the competition format (IBU, 2022a) (Table 1). The physiological demands are intermittent, due to high-intensity skiing bouts being interspersed with low-intensity shooting bouts. This is exemplified by mean heart rate (HR_{mean}), which has been measured as ~ 90% of maximal heart rate (HR_{max}) during the skiing bouts and ~ 60–70 of HR_{max} during the shooting bouts (Hoffman & Street, 1992). A typical heart rate (HR) profile for the pursuit competition format is shown in Figure 4. The speed profile is also displayed, which changes due to the topography of the competition course, while HR remains relatively stable during the skiing bouts (Figure 4).

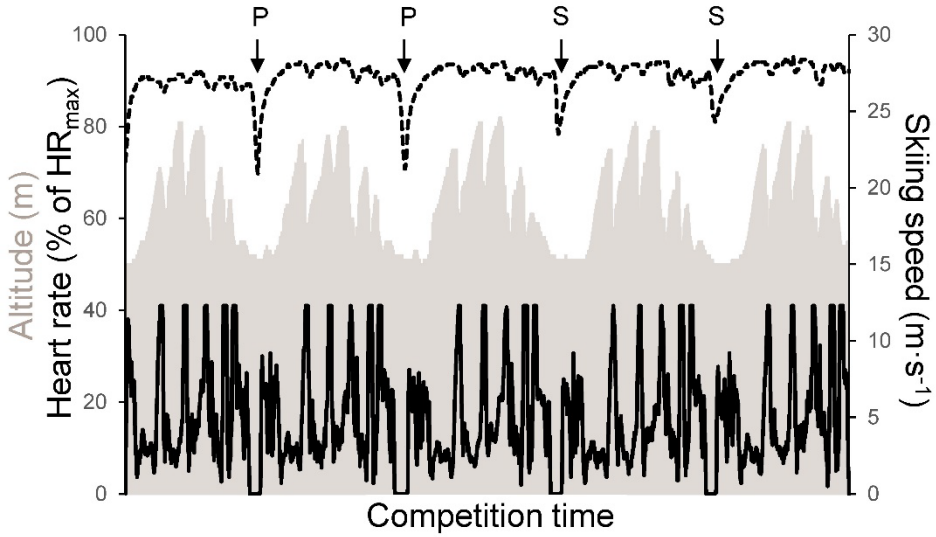

Figure 4. Relative heart rate (dotted black line) and skiing speed (solid black line) for one World Cup athlete during the pursuit competition format, in relation to the course profile (shaded grey area). The arrows mark the time of the prone (P) and standing (S) shooting bouts. Data are provided by the Swedish Biathlon Federation.

According to Joyner and Coyle (2008), three main physiological factors play a key role for general endurance performance; maximal oxygen uptake ($\dot{V}O_{2max}$), the workload at the lactate threshold (LT) and the efficiency of movement. These factors, together with anaerobic energy contribution, also seem to be important for biathlon skiing performance (Laaksonen et al., 2020), which will be further discussed in sections 1.4.1–1.4.4.

1.4.1 Maximal oxygen uptake

$\dot{V}O_{2max}$ represents an individual's aerobic capacity and is affected by the integrative capacities of cardiac output, total body hemoglobin, muscle blood flow (e.g., capillary density, blood volume and viscosity) and muscle oxygen (O_2) extraction (e.g., mitochondria density, enzyme activity and peripheral diffusion gradient) (Bassett & Howley, 2000; Kanstrup & Ekblom, 1984; Mitchell et al., 1958; Saltin & Strange, 1992). In XC skiing, the upper and lower body work simultaneously and sub-techniques that activate higher volumes of muscle masses (i.e., whole-body work) produce higher values for $\dot{V}O_{2max}$ compared to sub-techniques that activate smaller muscle masses (Holmberg, 2015; Holmberg et al., 2007). Elite biathletes and XC skiers have demonstrated absolute $\dot{V}O_{2max}$ values of > 4 and 6 $L \cdot min^{-1}$ for women and men, respectively (Holmberg, 2015; Tønnessen et al., 2015). These correspond to values relative to body mass of ~ 70 and 80 $mL \cdot kg \cdot min^{-1}$ (Holmberg, 2015; Saltin & Astrand, 1967; Tønnessen et al., 2015), which makes biathlon and XC skiing two of the sports with the highest measured relative $\dot{V}O_{2max}$ values, together with distance running and cycling (Impellizzeri et al., 2005; Saltin & Astrand, 1967). Elite XC skiers have shown elevated values for all steps involved in the O_2 transport chain compared to the normal population, such as cardiac output (Ekblom & Hermansen, 1968),

total body hemoglobin (Lundgren et al., 2015; Zelenkova et al., 2019), capillary density of the muscles in the upper and lower body (Mygind, 1995; Parsons et al., 1993; Ørtenblad et al., 2018) and mitochondrial volume (Ørtenblad et al., 2018). $\dot{V}O_{2max}$ has also been shown to relate to biathlon (Laaksonen et al., 2020; Rundell, 1995; Rundell & Bacharach, 1995) and XC skiing performance (Sandbakk et al., 2011a; Shang et al., 2022; Talsnes et al., 2021), determined as competition skiing speed/time or ranking points. However, it is unclear whether $\dot{V}O_{2max}$ is affected by rifle carriage in biathlon.

1.4.2 Lactate threshold

Endurance exercise lasting more than 10–15 min is typically performed at an internal intensity that does not reach $\dot{V}O_{2max}$ (Bassett & Howley, 2000; Costill et al., 1973). The fraction of $\dot{V}O_{2max}$ used during endurance events is to a great extent dependent on the LT (Joyner & Coyle, 2008). During moderate- and high-intensity exercise, the active muscle uses glycogen and glucose as fuels to a greater extent compared to low-intensity exercise, through both aerobic and anaerobic processes (glycogenolysis and glycolysis) (Holloszy & Coyle, 1984). Lactate is a bi-product of glycolysis and has previously been viewed as a contributing factor to muscle fatigue (Robergs et al., 2004), but in recent years has been shown to play an important role as a signaling molecule and energetic substrate, as well as serving as a gluconeogenic precursor (Brooks et al., 2022; Certo et al., 2022; Poole et al., 2021). The LT is defined as the point where the blood lactate concentration (BLa) starts to increase rapidly and is determined mainly by the oxidative capacity of the muscle (Holloszy & Coyle, 1984). The LT can be determined using a wide range of methods, such as fixed BLa values, increases in BLa above resting values, or individually set thresholds (determined by the tangent of the BLa

curve) (Faude et al., 2009). A fixed value of 4 mmol·L^{-1} of BLa (onset of blood lactate accumulation; OBLA) and individually set thresholds are commonly used in biathlon and XC skiing research. Elite and well-trained biathletes and XC skiers have demonstrated LTs at intensities > 80% of their $\dot{V}O_{2max}$ (Johansen et al., 2022; Laaksonen et al., 2020; Rundell, 1995; Welde et al., 2003), which is comparable to other endurance trained athletes (Joyner & Coyle, 2008). The speed or $\dot{V}O_2$ at LT or OBLA have also been shown to be related to performance (i.e., competition speed/time and/or ranking points) in biathlon and XC skiing (Carlsson et al., 2012; Jones et al., 2021; Laaksonen et al., 2020; Larsson et al., 2002; Rundell, 1995; Rundell & Bacharach, 1995; Sandbakk et al., 2011c; Shang et al., 2022) and have been reported to explain 30–35% of the variance in biathlon skiing performance (Laaksonen et al., 2020). This emphasizes the importance of a high LT for biathlon skiing performance, but the effect of rifle carriage on the LT is not yet investigated.

1.4.3 Anaerobic energy contribution

In biathlon competitions, the course profile is required to consist of continuously changing flat, uphill and downhill sections (IBU, 2022b), which impacts upon the metabolic demands and challenges the energy contribution from aerobic pathways. Therefore, the contribution of the anaerobic energy system is increased when the aerobic energy supply is not sufficient to cover the metabolic demand (i.e., O_2 demand > 100% $\dot{V}O_{2max}$). Previous studies have estimated the O_2 demand to be 110–160% of $\dot{V}O_{2max}$ in uphill terrain during a 13.5 km simulated XC skiing competition, with the highest demands during shorter uphill sections (lasting < 30 s) (Gløersen et al., 2020; Karlsson et al., 2018). Similar work rates in uphill terrain have also been observed in XC skiing sprint (~ 1.3 km) (Andersson et al., 2017;

Andersson et al., 2019), with a total anaerobic energy contribution of 17–26% during skiing events lasting ~ 3 min (Andersson et al., 2017; Andersson et al., 2016; Losnegard et al., 2012; Losnegard et al., 2013; McGawley & Holmberg, 2014). Most likely, the anaerobic energy contribution in skiing is largely dependent on course profile and pacing pattern of the athlete, and not the race duration itself (Losnegard, 2019). Although the total anaerobic energy contribution in biathlon and XC skiing competitions is relatively small, it can still be an important factor for performance in sections with high power output (PO), such as the uphills and finishing spurts. Previous studies have shown a correlation between performance in XC skiing and anaerobic energy contribution (Losnegard et al., 2012), and the total O_2 deficit during a simulated XC skiing sprint explained ~ 15% of the variance in overall performance (Andersson et al., 2017).

1.4.4 Gross efficiency

Gross efficiency (GE) is the most commonly used measure of efficiency in biathlon and XC skiing research and is calculated as the ratio of the PO performed relative to energy expenditure (Coyle, 1999; Joyner & Coyle, 2008; Serresse et al., 1988). Previous research indicates that when PO can be determined, GE provides a more reliable measurement of whole-body efficiency in endurance sports compared to other calculations and measurements (Ettema & Lorås, 2009). Physiological factors that can affect efficiency of movement include muscle fiber type (Coyle et al., 1992), speed of movement (Cavanagh & Kram, 1985; Powers et al., 1984) and exercise intensity (Cavanagh & Kram, 1985; Donovan & Brooks, 1977; Powers et al., 1984). Efficiency is also related to the energy substrate used during submaximal exercise, with more efficient individuals using blood-borne free-fatty acids as a fuel to a higher extent, and thereby likely

sparing intramuscular energy sources, compared to their less efficient counterparts (Laaksonen et al., 2018c). Biomechanical factors (e.g., technique) also contribute to GE (Anderson, 1996; Sandbakk et al., 2010), but the published research regarding this in XC skiing is limited. In biathlon and XC skiing, the GE is usually ~ 14–18 % (Carlsson et al., 2021; Laaksonen et al., 2020; Luchsinger et al., 2019b; Sandbakk et al., 2011a), with faster and more senior skiers demonstrating higher efficiency than their slower and younger counterparts (Ainegren et al., 2013; Sandbakk et al., 2010; Sandbakk et al., 2011b). GE is also related to biathlon and XC skiing speed and/or ranking points (Laaksonen et al., 2020; Sandbakk et al., 2013; Sandbakk et al., 2011b). In one study of well-trained XC skiers, GE has been shown to be the strongest predictor of XC skiing sprint performance (Andersson et al., 2017).

1.4.5 Sex differences

Studies performed on female athletes have been limited, historically, and during the years 2014–2020 the proportion of female participants included in papers published in six major sport and exercise science journals was ~ 34% (Cowley et al., 2021). Previous research has shown that competition skiing speed is 12–15% slower in female biathletes (Luchsinger et al., 2018; Luchsinger et al., 2019a) and ~ 9–12% slower in female XC skiers (Andersson et al., 2019; Bolger et al., 2015) compared to the men, with the largest sex differences (14–19%) measured during uphill skiing (Andersson et al., 2019; Bolger et al., 2015). Male biathletes and XC skiers have elicited ~ 14–18% higher relative values for $\dot{V}O_{2max}$ ($mL \cdot kg \cdot min^{-1}$) compared to women (Bolger et al., 2015; Jones et al., 2021; Laaksonen et al., 2020; Sandbakk et al., 2012b; Tønnessen et al., 2015) and this is probably due to the higher total body hemoglobin (Calbet & Joyner, 2010; Sandbakk et al., 2012b;

Zelenkova et al., 2019) and muscle mass (Hegge et al., 2016; Jones et al., 2021) in men. Female biathletes and XC skiers also demonstrate lower absolute $\dot{V}O_2$ and skiing speeds at LT and/or OBLA than their male counterparts (Johansen et al., 2022; Jones et al., 2021; Laaksonen et al., 2020; Larsson et al., 2002; Sandbakk et al., 2012b), while no difference is shown between the sexes for $\dot{V}O_2$ at LT relative to $\dot{V}O_{2max}$ (Johansen et al., 2022; Laaksonen et al., 2020; Larsson et al., 2002). No difference has been shown between the sexes for accumulated O_2 deficit ($\sum O_2$ deficit) (Laaksonen et al., 2020; McGawley & Holmberg, 2014), which is used to express the absolute anaerobic energy production, while the relative anaerobic energy contribution seems to be lower in female compared to male XC skiers (McGawley & Holmberg, 2014), which is explained by the higher aerobic energy contribution (i.e., $\dot{V}O_2$) in men. In addition, no sex differences have been found for GE in biathlon or XC skiing (Hegge et al., 2015; Laaksonen et al., 2020; Sandbakk et al., 2012b; Sandbakk et al., 2013). Thus, there are physiological differences between the two sexes, but no previous study has investigated whether rifle carriage in biathlon affects physiological variables differently for female and male biathletes.

1.5 Biomechanical determinants of biathlon skiing performance

1.5.1 The skating technique

Since the middle of the 1980s, skating has been the only XC skiing technique used in biathlon competitions. The skating technique consists of multiple sub-techniques, often referred to as ´gears´ (Nilsson et al., 2004). In elite biathlon and XC skiing, gears 2–5 are most commonly used and selected according to skiing speed and terrain (Nilsson et al., 2004) (Figure 5).

Gear 2 (also named V1 skate) is used in steep uphill terrain and is characterized by one asymmetrical pole action for every second leg action. In gear 2, skiers typically prefer one side to lean on during pole plant (PP). However, the choice of dominant side cannot be explained by anthropometric/biomechanical factors or dominant hand or leg side, suggesting that this preference is highly specific to the exercise task (Stöggl et al., 2013).

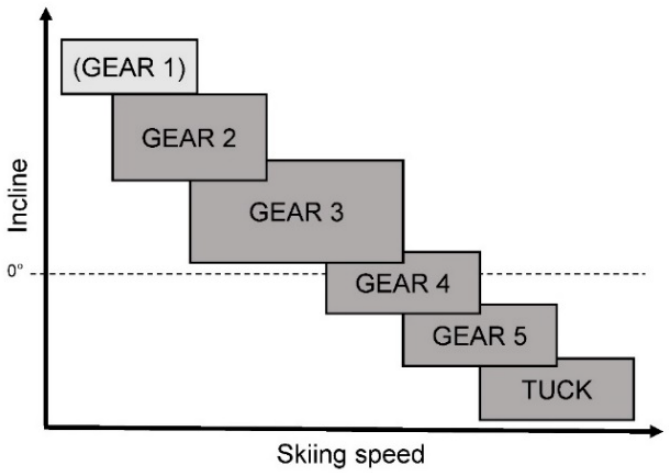

Figure 5. Use of gears 1–5 and tuck skiing in relation to skiing speed and incline (adapted from Losnegard, 2019). Gear 1 is not normally used by elite skiers.

Gear 3 (also named V2 skate) is typically used in moderate uphill and flat terrain and is a symmetrical gear, with one pole action for every leg action. Gear 4 (also named V2 alternate skate) has a symmetrical poling action for every second leg action and is used in flat and lighter downhill terrain. Gear 5 involves skating with the legs only, without a poling action, and is used in moderate downhill terrain. Finally, the tuck position is used in steeper downhill terrain and at high speeds and involves no pole or leg actions. Previous research has shown that male XC skiers change gears ~ 30 times during a XC skiing sprint competition (~ 1300 m) (Andersson et al., 2010).

Illustrations of gears 2–5 are shown in Figure 6.

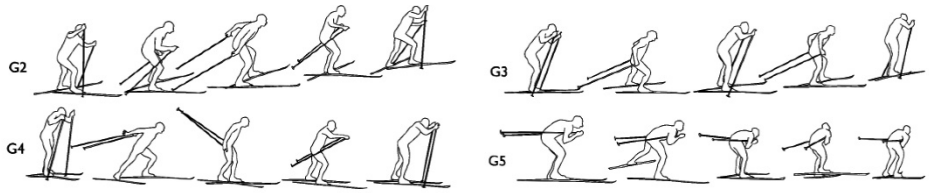

Figure 6. The different sub-techniques, gears (G) 2–5, used in skate cross-country skiing. This figure is presented in Andersson et al. (2010) and Andersson (2016) and is used here with permission from the first author .

Biomechanics in biathlon (i.e., skiing with a rifle) has been sparsely studied. As such, this section is to a large extent based on research performed on XC skiing, while rifle carriage in biathlon will be further discussed in section 1.6.3.

1.5.2 Kinematics

The majority of research investigating the biomechanics of the skating technique has focused on cycle characteristics. Cycle length (CL) and/or cycle rate (CR) increase with speed during both roller-skiing and on-snow skiing (Ohtonen et al., 2018; Sandbakk et al., 2012a; Stöggl et al., 2015; Stöggl & Holmberg, 2015; Stöggl et al., 2011; Stöggl & Müller, 2009) and a longer CL is related to improved performance (Bilodeau et al., 1996; Losnegard et al., 2012; Nilsson et al., 2004; Sandbakk et al., 2011a; Sandbakk et al., 2010; Smith & Heagy, 1994; Stöggl et al., 2011). A decrease in CR is explained by shorter poling times (Stöggl et al., 2015; Stöggl & Holmberg, 2015; Stöggl et al., 2011; Stöggl & Müller, 2009), and in some studies also by decreased swing times (Stöggl & Holmberg, 2015; Stöggl et al., 2011), which may be affected by the faster skiing speed and/or the sub-technique used.

Few studies have investigated how the movement of different body segments are related to skate skiing speed. At increased speeds (submaximal to maximal) in gear 3, the range of motion (ROM) increases in hip and knee flexion/extension and enhances the vertical movement of the center of mass (COM) (Ohtonen et al., 2016). In addition, faster skiers have demonstrated a more forward lean of the upper body at PP (Losnegard et al., 2017), increased ROM in shoulder flexion/extension movement (Losnegard et al., 2017) and a better timing of the vertical movement of the COM (Gløersen et al., 2018) compared to their slower counterparts. As a result of this, faster XC skiers reach a more upright body position at PP, which is probably beneficial to use the body mass to exert force on the poles. Moreover, a more vertical position of the poles at PP and smaller angles between the skis and the direction of movement seem to be beneficial for skiing performance in the skating technique (Zoppirolli et al., 2020). However, the effect of rifle carriage on skiing technique in biathlon has not been investigated.

1.5.3 Kinetics

In research investigating kinetic variables in XC skiing, pole and leg forces are normally measured. When skiing in gear 3, maximal/peak and delta forces (i.e., the difference between maximal and minimal forces measured) in the poles and legs are increased at higher speeds (Ohtonen et al., 2016; Stöggl et al., 2011). Faster skiers also demonstrate better timing of force application by the legs (Stöggl et al., 2011) and less pressure on the medial part of the foot in the beginning of the gliding phase (Pavailler et al., 2020) compared to slower skiers. One previous study has investigated the kinetics during biathlon skiing, demonstrating increased peak and impulse of forces in legs and poles with increased speeds (Stöggl & Holmberg,

2015), but it remains unknown whether these changes in kinetics are associated with biathlon skiing performance.

1.5.4 Gear distribution

As stated in section 1.5.1, biathletes and XC skiers use different gears depending on the skiing speed and incline of the terrain. Gear 3 is the most commonly used gear for male skiers during uphill skiing and overall in XC skiing, followed by gear 2 (Andersson et al., 2010; Shang et al., 2022). The use of gear 2 increases with the duration of skiing and the number of skiing laps (Andersson et al., 2010; Ardigò et al., 2020; Shang et al., 2022). In addition, gear distribution seems to change with competition level and age/training status, with faster and older (~ 22 years) skiers using gear 3 to a greater extent than their slower and younger (~ 14 years) counterparts (Andersson et al., 2010; Sollie et al., 2021) and a decreased use of gear 2 has been shown to enhance performance (Andersson et al., 2010). However, previous research has demonstrated that there is a turn-over point where gear 2 starts to be more efficient than gear 3, due to physiological factors such as HR, BLa and oxygen uptake ($\dot{V}O_2$) (Kvamme et al., 2005). According to Kvamme et al. (2005), gear 2 becomes more efficient to use at an incline of higher than ~ 4.2–4.8°. However, the turn-over point may also be affected by skiing speed, physical status, athlete sex, distance of the uphill and/or the friction between the skis and snow (depending on e.g., weather conditions, preparation of the course and skis/waxing). While gear distribution is associated with skiing performance, knowledge about the effect of rifle carriage on gear distribution during biathlon skiing is lacking.

1.5.5 Sex differences

Of the 24 studies regarding biomechanical variables and their relation to skiing performance in the skating technique included in a review

by Zoppirolli et al. (2020), 21 included only male skiers, one included both sexes and two included only women. The review included studies published over the last 25 years and demonstrates considerable inequality between sexes regarding participation in studies of skiing biomechanics.

On average, female skiers have less muscle mass compared to men, especially in the upper body (Hegge et al., 2016; Jones et al., 2021). Male skiers also have a greater proportion of their muscle mass located in the upper body compared to women, leading to a larger difference in PO between sexes for upper-body compared to lower- or whole-body work (Hegge et al., 2016; Sandbakk et al., 2012b). The differences between sexes in upper-body muscle mass and PO may affect the biomechanics of skiing, such as body position at PP and the use of the upper-body during the poling phase. The differences between sexes may be even larger for gears with a high involvement of the upper body. Gear 3 is more dependent on the upper body to produce PO compared to gear 2 (Millet et al., 1998c), which could affect the use of sub-techniques differently for female and male skiers. Women have been shown to use gear 2 to a greater extent in uphill terrain, while male skiers more often use gear 3 (Andersson et al., 2019), which probably results from the differences between sexes in upper-body muscle mass and PO. Stöggl et al. (2015) also demonstrated higher peak and impulse of pole forces (both 50% higher) in men compared to women during skiing, without differences in relative leg forces. Women create ~ 11–17% shorter CLs compared to men, without differences in CR (Andersson et al., 2019; Ardigò et al., 2020; Stöggl et al., 2015), which may be related to differences in body height. No previous study has investigated possible sex differences in the movements of body segments during

XC or biathlon skiing, yet increasing our knowledge of these factors would be useful to provide sex-specific feedback about technical factors, that may help skiers of both sexes to improve performance.

1.6 Load carriage

In some occupations load carriage is often required, e.g., for military personnel, fire fighters and police officers (Taylor et al., 2016; Vickery-Howe et al., 2021). Load carriage is also performed for recreational purposes, such as hiking (Vickery-Howe et al., 2021), and in sporting events, such as adventure races (Fagundes et al., 2017). Firefighters often carry loads of 20–25 kg (Taylor et al., 2016), while the load for police officers is normally less depending on the specific occupation. Soldiers carry heavier loads, sometimes of > 50 kg, and this mass has increased over the last 40 years (Taylor et al., 2016). Extensive research has investigated the effect of load carriage on physiological and biomechanical variables in soldiers, while other studies have investigated the responses to load carriage in active/endurance trained men and women. The response to load carriage depends upon many factors, such as the mass of the load and its distribution on the body, body mass and body composition of the carrier, speed of movement, incline and type of terrain, load carriage experience, sex and situational and environmental factors (Fallowfield et al., 2012; Haisman, 1988; Taylor et al., 2016).

Load can be carried in different ways, such as in a backpack, using a double-pack (where the mass is distributed on the back and front of the trunk), weight vest or webbing (a vest with the weight close to the waist), as body armor, a helmet and/or a weapon. In the majority of studies presented in sections 1.6.1 and 1.6.2, the external load is

carried around the trunk, which is consistent with rifle carriage in biathlon.

1.6.1 Physiological effects of load carriage

Previous research has shown that the energy cost of load carriage partly depends on where on the body the external mass is located, with the most efficient placement as close to the COM as possible (i.e., using a well-fitted backpack, double-pack or weight vest) (Boffey et al., 2019; Knapik et al., 2004; Taylor et al., 2016). It is also preferable to place the load higher up on the trunk when walking on even/flat terrain, while a lower placed load seems to be more efficient for uneven terrain (Boffey et al., 2019; Knapik et al., 2004). Previous research has also shown that more experienced load carriers have a higher efficiency, measured as the increase in $\dot{V}O_2$ from unloaded conditions, compared to inexperienced counterparts when carrying the same load (Godhe et al., 2020), and the coefficient of variation for efficiency during load carriage can be large (up to ~ 12%) (Hudson et al., 2020). Large inter-individual variation in energy cost has also been shown in biathlon (Rundell & Szmedra, 1998), suggesting that the individual response to load carriage may also differ between experienced load carriers.

Load carriage (of 6–40 kg and 30–70% of body mass) increases $\dot{V}O_2$, ventilation rate ($\dot{V}_E$), carbon dioxide production ($\dot{V}CO_2$), energy expenditure, HR and rating of perceived exertion (RPE) at submaximal intensities (Armstrong et al., 2019; Beekley et al., 2007; Boffey et al., 2019; Hudson et al., 2020; Looney et al., 2021; Lyons et al., 2005; Peoples et al., 2016; Phillips et al., 2016b; Pihlainen et al., 2014; Quesada et al., 2000; Vickery-Howe et al., 2020; Vickery-Howe et al., 2021). $\dot{V}O_2$ increases linearly with the increase in carried load for inclines up to 4% during walking, with a more rapid increase in

$\dot{V}O_2$ at higher inclines (Phillips et al., 2016a). At higher intensities (> 50% of $\dot{V}O_{2max}$) $\dot{V}_E$ seems to increase more rapidly in relation to the carried load (Borghols et al., 1978). Since biathlon is a whole-body exercise performed at high intensities and in varying terrain, the effect of rifle carriage on respiratory variables in biathlon should be investigated further.

The LT and ventilatory thresholds in adventure racers and active men occur at lower intensities (i.e., a lower absolute speed or $\dot{V}O_2$) during load carriage compared to unloaded conditions (Fagundes et al., 2017; Phillips et al., 2016a) and the LT is also related to physical performance when carrying a load (8 miles running with 20 kg) (Simpson et al., 2017). At submaximal intensities, load carriage also increases breathing frequency and/or decreases tidal volume in soldiers and active/endurance trained men (Armstrong et al., 2019; Peoples et al., 2016; Phillips et al., 2016a; Phillips et al., 2016b), which may lead to a higher rate of fatigue in the respiratory muscles compared to unloaded conditions (Armstrong et al., 2019; Faghy & Brown, 2014; Phillips et al., 2016b).

The effect of load carriage on physiological variables at maximal intensities is conflicting. It is clear that performance (e.g., time to exhaustion/time to complete a task) is impaired during load carriage in active/endurance trained men and women (Peoples et al., 2016; Phillips et al., 2016a; Walker et al., 2015; Wang et al., 2021). However, some studies have shown that $\dot{V}O_{2max}$, HR_{max} and/or maximal $\dot{V}_E$ ($\dot{V}_{Emax}$) are decreased during load carriage (Peoples et al., 2016; Phillips et al., 2016a; Walker et al., 2015), while other studies did not find any differences in $\dot{V}O_{2max}$ or HR_{max} in loaded compared to unloaded conditions (Fagundes et al., 2017; Wang et al., 2021). Exercise tasks that rely more on the anaerobic energy system also

seem to be affected by load carriage. For example, soldiers demonstrated that 30-m sprint time increased during load carriage (21.6 kg), with more than half of the time loss occurring during the first 5 m of running when starting from a prone position (Treloar & Billing, 2011). Moreover, maximal BLa (BLa_{max}) was lower after a 2.5 km time trial (TT) when active men carried 25 kg compared to an unloaded condition (Faghy & Brown, 2014). Together, these findings suggest that load carriage seems to impair anaerobic performance by reducing acceleration speed and anaerobic glycolysis. This may have an negative impact on biathlon skiing performance, since anaerobic energy contribution seems to be an important factor for biathlon skiing performance (Laaksonen et al., 2020).

1.6.2 Biomechanical effects of load carriage

Both increased absolute and relative masses of the load have been shown to decrease CL and/or increase CR during walking or running (Baggaley et al., 2020; Bode et al., 2021; Harman et al., 2000; LaFiandra et al., 2003; Martin & Nelson, 1986; Seay, 2015). However, some studies show no differences in CL or CR during load carriage compared to unloaded conditions (Almonroeder et al., 2021; Mullins et al., 2015). Load carriage also increases ground contact time for each foot and the time both feet are in contact with the ground (Grenier et al., 2012; Harman et al., 2000; Ling et al., 2004; Middleton et al., 2022; Rice et al., 2017; Seay, 2015; Silder et al., 2013; Sousa et al., 2022; Vickery-Howe et al., 2021), probably in order to stabilize the external load. This may also have an effect on biathlon skiing, since a large part of the skiing cycle is spent on one ski and requires transfer of the body mass from one side to the other repeatedly. Increased time where both skis have contact with the ground/snow due to impaired

balance caused by rifle carriage may therefore interrupt the gliding phase and impair biathlon skiing performance.

Load carriage affects the kinematics of walking and running by increasing forward trunk inclination (flexion) compared to lighter loads or unloaded conditions (Attwells et al., 2006; Brown et al., 2014; Harman et al., 2000; Krupenevich et al., 2015; Liew et al., 2020; Ling et al., 2004; Majumdar et al., 2010; Martin & Nelson, 1986; Seay, 2015; Walsh & Low, 2021). This change in body position is probably performed to move the COM of the external load closer to the COM of the body (Brown et al., 2014; Walsh & Low, 2021), thereby increasing stability. However, it is still unclear how load carriage affects the body position during highly technical whole-body movements like biathlon and XC skiing.

Several studies have shown that peak hip flexion and ROM in hip flexion/extension increases with load (Bode et al., 2021; Harman et al., 2000; Loverro et al., 2019; Majumdar et al., 2010; Middleton et al., 2022; Morrison et al., 2019; Seay, 2015; Silder et al., 2013; Sousa et al., 2022; Unnikrishnan et al., 2021; Vickery-Howe et al., 2021; Walsh & Low, 2021), which is probably a result of a forward tilt and/or less flexion/extension of the pelvis (LaFiandra et al., 2003; Liew et al., 2020; Sousa et al., 2022) to be able to maintain CL to a higher extent. Some studies have also shown that load carriage increases the peak hip adduction angle and abduction/adduction ROM in the hips (i.e., a broader step width) to increase stability of the carrier (Birrell & Haslam, 2009; Loverro et al., 2019). If load carriage were also to increase step width during biathlon skiing, it may have a negative impact on skiing performance since a larger angle between the ski and the direction of movement has been shown to be negatively associated with skiing speed (Zoppirolli et al., 2020).

Load carriage increases the load on the lower body and force production in the lower limbs compared to unloaded walking or running (Birrell et al., 2007; Brown et al., 2014; Quesada et al., 2000; Rice et al., 2017; Unnikrishnan et al., 2021), with the associated increase in ground reaction force being linear to the mass of the load (Birrell et al., 2007). Muscle activation determined using electromyography (EMG) signals also increases during load carriage exercises, particularly in the back (erector spinae), thighs (rectus femoris, vastus medialis and lateralis) and calves (gastrocnemius medialis) (Paul et al., 2016; Rice et al., 2017; Walsh & Harrison, 2021; Walsh & Low, 2021). These studies have all focused on lower-body exercise (i.e., walking or running) and it is unclear if changes in kinetics due to load carriage also affects the kinematics (i.e., movement/technique) during whole-body exercise (e.g., XC skiing).

Load carriage research in walking and running is extensive but there are some conflicting results. This is probably due to differences in the mass of the load investigated (in absolute terms or relative to body mass), the speed and/or duration of the exercise, the physical status of the participants and their experience of load carriage, testing protocols and measurements. It is also unknown how lighter loads (e.g., the rifle used in biathlon) may affect physiological and biomechanical variables during highly technical whole-body exercise on snow (e.g., XC skiing).

1.6.3 Rifle carriage in biathlon

In contrast to the military setting, the mass of the load carried in biathlon is much lighter (normally 3.5–4.0 kg) and is always carried on the back. Biathlon skiing involves whole-body exercise (compared to lower-body walking or running) and biathletes normally have a higher endurance capacity compared to soldiers or active men and

women participating in the studies presented in sections 1.6.1 and 1.6.2. Prior to the commencement of this thesis, only two studies had investigated the effects of rifle carriage on physiological and biomechanical variables in biathlon. These studies showed that skiing with a rifle (WR) increases $\dot{V}O_2$, $\dot{V}_E$, BLa (for intensities around or above LT) and HR during roller-skiing at submaximal intensities compared to skiing without a rifle (NR) (Rundell & Szmedra, 1998; Stöggl et al., 2015), while GE remained unchanged (Stöggl et al., 2015). The variation in energy cost between individuals also seems to increase when skiing WR, which is suggested to be a result of the difference in the mass of the rifle relative to body mass (Rundell & Szmedra, 1998). From a biomechanical perspective, previous research has shown that cycle time (CT) and CL decreases, while CR and peak leg force increases when skiing WR compared NR (Stöggl et al., 2015).

The two previous studies that have investigated rifle carriage in biathlon were performed using roller-skiing at submaximal intensities and estimated competition speeds (Rundell & Szmedra, 1998; Stöggl et al., 2015). However, questions still remain regarding the effect of rifle carriage on roller-skiing and on-snow skiing performance, speed at LT, anaerobic energy contribution, kinematics (e.g., ROM in different body joints) and gear distribution during biathlon skiing.

1.6.4 Sex differences

The majority of published articles in the military setting have only included male participants. During the last 10 years, the number of female soldiers has increased due to changed army directives in e.g., the USA in 2016 (Bode et al., 2021). Since the absolute mass of load carriage is normally the same for all soldiers (e.g., 25–70 kg, depending on the mission and occupation), women will, on average,

carry heavier relative loads due to their lower body mass (Wendland et al., 2022).

Previous research has shown that women work at a higher percentage of their $\dot{V}O_{2max}$ and a higher absolute HR compared to men when walking with a load at matched speeds (Vickery-Howe et al., 2020). In contrast, men have demonstrated higher lean body masses (i.e., muscle mass) and strength in the lower body, which may also affect load carriage exercises (Nindl et al., 2016). During walking, women have a higher CR and lower CL compared to men when walking at matched speeds (Middleton et al., 2022; Vickery-Howe et al., 2020), and this is probably due to differences in leg length. Women also demonstrate larger changes in CL and CR, and a greater decrease in 30-m sprint performance due to load carriage than men (Martin & Nelson, 1986; Treloar & Billing, 2011). In addition, women elicited a greater forward lean in the trunk (Krupenevich et al., 2015) and smaller knee flexion/extension ROM (Bode et al., 2021; Loverro et al., 2019) during load carriage, while men increase peak hip adduction more than women (Loverro et al., 2019). Other studies have shown no sex differences in joint ROM or muscle activation pattern due to load carriage (Larsson et al., 2022; Middleton et al., 2022; Silder et al., 2013; Vickery-Howe et al., 2020).

In biathlon, the absolute mass of the rifle is the same for women and men, which generally gives a higher relative load of the rifle for female biathletes (Rundell & Szmedra, 1998). The increase in $\dot{V}O_2$ and $\dot{V}_E$ due to rifle carriage has been shown to be larger in female compared to male biathletes (Rundell & Szmedra, 1998; Stöggl et al., 2015), and this may be due to the difference in relative load between the sexes. However, it remains unclear whether rifle carriage in

biathlon affects performance and other physiological or biomechanical variables similarly for women and men.

1.7 Biathlon training

Laaksonen et al. (2018b) reported that elite Swedish biathletes perform 700–900 hours of physical training·year^{-1}, divided into high- (5–6%), moderate- (4–5%) and low-intensity endurance training (~ 80%) and 10% of strength and speed training. In addition to the physical training, elite biathletes fire ~ 22 000 shots·year^{-1}, with ~ 12 000 of these shots fired in combination with physical training (Laaksonen et al., 2018b). Myakinchenko et al. (2020) and Østerås et al. (2013) reported that Russian men and women and Norwegian women performed ~ 500 h·year^{-1} of endurance-based training, with Myakinchenko et al. (2020) demonstrating similar distributions between high-, moderate- and low-intensity training (~ 4%, 7% and 89%) as Laaksonen et al. (2018b). Ten years of training data for one of the best male biathletes of all time showed an annual physical training volume of ~ 530–700 hours, divided into high- (~ 4%), moderate- (~3%) and low-intensity training (~ 86%) and ~ 6% of strength training (Schmitt et al., 2020). In biathlon, approximately 50–60% of the endurance training is performed as sport-specific training, i.e., roller-skiing or on-snow skiing in the skating or classic technique (Laaksonen et al., 2018b; Myakinchenko et al., 2020; Schmitt et al., 2020). The volume of sport-specific training presented by Østerås et al. (2013) are slightly lower, although their data only included roller-skiing and on-snow skiing in the skating technique. No study has presented the amount of endurance training that includes rifle carriage, although coaches at the Swedish Biathlon Federation estimated that the proportion would be 15–20% (Laaksonen et al., 2018b).

1.8 Training to improve load carriage performance

Several training intervention studies have been performed in a military setting to improve TT performance when walking or running with a load. A combination of endurance and strength training at least 3 times·week^{-1} for a minimum of 4 weeks has been shown to improve load carriage performance in untrained or moderately trained participants (Knapik et al., 2012). If at least one of the endurance-based training sessions·week^{-1} included load carriage exercises, the improvement in performance was enhanced further (Dicks et al., 2021; Knapik et al., 2012). High-intensity running (4 × 3 min twice per week) improved performance in a 3.2 km loaded running test (using a 21-kg load) by ~ 5%, although the improvement was even larger (~ 10%) when carrying loads during one of the high-intensity training sessions·week^{-1} (Dicks et al., 2021). Similarly, 10 weeks of training (endurance, strength and load carriage exercises) improved performance during a 3.2 km loaded run (using a 15-kg load) by ~ 7% (Williams & Rayson, 2006). Moreover, after 10 weeks of physical training including two load carriage sessions· week^{-1}, $\dot{V}O_2$ decreased during submaximal walking with an indication of a shift towards larger fat utilization by a reduction in respiratory exchange ratio (RER) during a 5 km loaded walk (using a 23-kg load) (Wills et al., 2020). Using a similar training intervention involving 10 weeks of weighted walking and resistance training, lower-body strength increased and RPE during submaximal load walking decreased (Wills et al., 2019; Wills et al., 2021). All studies mentioned above included participants described as healthy or recreationally active, and who were relatively inexperienced load carriers before the start of the intervention. For inexperienced load carriers and/or untrained participants, one additional training session·week^{-1} including load

carriage exercise seems to be sufficient to improve load carriage performance. However, there is still a lack of knowledge regarding the effects of load carriage training in well-trained athletes, especially in biathlon.

2 Rationale

The sport of biathlon has developed during the last decades with increased skiing speeds, but also smaller margins between biathletes in World Cup and World Championship competitions. During the competition season of 2021/2022 the mean time difference between athletes placed 3rd and 4th in individual World Cup competitions were 5.7 and 4.7 s for sprint, 14.3 and 10.7 s for individual, 10.8 and 17.3 s for pursuit and 7.4 and 9.3 s for mass-start competitions for women and men, respectively (IBU, 2022a). This corresponds to 0.3–0.9% of total competition time, which demonstrates the small differences between winning a medal or not at the highest international level. These small differences in performance between biathletes at the top level also highlight that minor details could potentially be of the highest importance to success.

Even though the research regarding factors important for XC skiing performance is quite extensive, research investigating skiing while carrying a rifle is lacking. It is still unclear how rifle carriage in biathlon affects specific physiological factors (e.g., speed at LT and anaerobic energy contribution), biomechanical variables (e.g., ROM in different body joints and gear distribution) and roller-skiing and on-snow skiing performance. It is also unclear whether women and men respond similarly to rifle carriage during biathlon skiing. In light of the unique demands in biathlon, improved knowledge of the effects of rifle carriage on biathlon skiing may lead to development and optimization of the sport-specific training, which can lead to improved overall performance.

3 Aims

The overall aim of this thesis was to investigate how rifle carriage in biathlon affects physiological and biomechanical variables related to skiing performance, as well as possible sex differences associated with rifle carriage.

The specific aims of each individual study were as follows:

Study I To investigate whether physiological factors are affected by rifle carriage during biathlon skiing performance, as well as possible sex differences associated with rifle carriage.

Study II To investigate whether an increased amount of training while carrying the rifle affects the physiology and performance of biathlon skiing in well-trained biathletes.

Study III To investigate how rifle carriage and skiing speed during biathlon roller-skiing affect ROM in joint angles and equipment (skis and poles) and body position, as well as possible sex differences associated with rifle carriage.

Study IV To investigate whether rifle carriage affects gear distribution during on-snow skiing in well-trained biathletes, and whether there were any associated sex differences. A second aim was to investigate whether gear distribution was related to biathlon skiing performance.

4 Methods

4.1 Participants

In this body of work a total number of 65 biathletes participated in the four studies. Eleven of the biathletes participated in two of the studies, with nine biathletes participating in both *Studies I* and *II*. In total, 46% of the participants were women. The characteristics of the participants in the different studies are presented in Table 2. According to the participant classification framework presented by McKay et al. (2022), the biathletes represented tier 4 (elite/international level, i.e., the majority of participants in *Studies I–III*) or tier 3 athletes (highly trained/national level, i.e., the majority of participants in *Study IV* and some participants in *Studies I–III*).

Table 2. Participant characteristics for Studies I–IV. Data is presented as mean ± SD.

	Sex	N	Age (years)	Body height (m)	Body mass (kg)	Rifle mass (kg)	Rifle mass (% of BM)
Study I	Women	9	21 ± 1	1.70 ± 0.04	66.3 ± 4.7	3.7	5.6 ± 0.4
	Men	8	25 ± 4*	1.81 ± 0.09*	73.6 ± 6.5*	3.7	5.0 ± 0.4*
Study II	Women	9	22 ± 3	1.69 ± 0.04	66.0 ± 4.8	3.7	5.6 ± 0.4
	Men	8	22 ± 2	1.80 ± 0.05*	74.5 ± 2.8*	3.7	5.0 ± 0.2*
Study III	Women	6	26 ± 3	1.69 ± 0.04	66.4 ± 4.2	3.9 ± 0.1	6.1 ± 0.4
	Men	8	25 ± 6	1.78 ± 0.07	77.2 ± 6.9*	4.1 ± 0.3	5.4 ± 0.4*
Study IV	Women	11	19 ± 2	1.67 ± 0.07	68.3 ± 9.9	4.1 ± 0.2	6.1 ± 1.0
	Men	17	19 ± 3	1.81 ± 0.05*	74.0 ± 6.2	4.0 ± 0.2	5.5 ± 0.6*

BM = Body mass

* *= Significantly different to women, $p < 0.05$.*

All studies were pre-approved by the Regional Ethical Review Board of Umeå University, Umeå, Sweden (*Study I* #2018-1222-31M; *Study*

III #2012-171-31M; *Study IV* 2016-50631M) or the Swedish Ethical Review Authority (*Study II* #2019-04527).

4.2 Overview of studies

Studies I and *II* included physiological measurements in the laboratory, while *Studies III* and *IV* investigated biomechanical effects of rifle carriage in the laboratory (*Study III*) or on snow in a field setting (*Study IV*). A brief overview of the four studies are presented in Table 3.

Table 3. Overview of Studies I–IV with focus area and type of exercise performed during testing.

	Focus	**Exercise mode**	**Type of trial**
Study I	Physiology	Roller-skiing (treadmill)	Submaximal workloads; Maximal time trial (W 900 m, M 1000 m)
Study II	Physiology (training intervention)	Roller-skiing (treadmill)	Submaximal workloads; Maximal time trial (W 900 m, M 1000 m)
Study III	Biomechanics (kinematics)	Roller-skiing (treadmill)	Submaximal workloads; Simulated competition speed
Study IV	Biomechanics (gear distribution)	On-snow skiing (field)	Maximal time trial (2230 m)

W = Women; M = Men

4.2.1 Physiological testing (*Studies I–II*)

All tests in *Studies I* and *II* were performed as treadmill roller-skiing using the gear 3 skating sub-technique. In *Study I*, participants visited the laboratory twice, with 2–6 days between the tests. One test occasion was performed as roller-skiing WR and the other one NR in a counter-balanced and randomized order. The same test protocol was performed on both test occasions, consisting of 3–5 submaximal

workloads and a maximal TT. Respiratory variables and HR were measured throughout the test, while BLa and RPE were recorded immediately after every performed workload.

In *Study II*, participants were tested before and after a training intervention lasting a minimum of 12 weeks. Pre- and post-tests consisted of 3–6 submaximal workloads NR in addition to two submaximal workloads and a maximal TT WR. During testing, respiratory variables and HR were measured throughout, while BLa and RPE were recorded immediately after every performed workload. During the training period, the intervention group (IG; n = 10) aimed to perform two additional training sessions per week (during their normal training program) while carrying the rifle. The control group (CG; n = 7) followed their normal training program.

4.2.2 Biomechanical testing (*Studies III–IV*)

In *Study III*, participants visited the laboratory twice to complete treadmill roller-skiing tests. On the first day of testing, peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) was determined for gears 3 and 2 (these values are presented in Stöggl et al., 2015). On the second day of testing, the participants completed one submaximal workload and one workload at simulated competition speed each for WR and NR (in a randomized and counter-balanced order). This protocol was performed first in gear 3 then in gear 2 in both WR and NR conditions. During testing, kinematic three-dimensional (3D) data were collected.

In *Study IV*, tests were performed as on-snow skiing with each participant tested on a single day. Participants skied a 2230-m TT at competition speed twice, once WR and once NR in a randomized and

counter-balanced order. During testing, participants were equipped with a portable 3D motion analysis system.

4.3 Protocols, measurements and equipment

4.3.1 Physiological testing (*Studies I–II*)

4.3.1.1 Protocols

In *Study I*, participants performed a standardized warm-up by roller-skiing at the same workload as for the first submaximal exercise level in the subsequent test. The submaximal test started at a velocity of 1.94 $m \cdot s^{-1}$ and 2.22 $m \cdot s^{-1}$ for women and men, respectively. Each workload lasted 4 min and the speed increased by 0.56 $m \cdot s^{-1}$ for every workload. Between each workload, the treadmill was stopped for 60 s and BLa and RPE were measured. The incline of the treadmill was constant during the submaximal test and the maximal TT, at 3.5° for women and 4.5° for men, respectively. The submaximal test was terminated when it was estimated from the RER, $\dot{V}_E / \dot{V}O_2$ ratio and HR that the participants had passed the LT. After 14 min of active and passive recovery, participants commenced a maximal TT (900 m for women, 1000 m for men) as fast as possible, controlling the speed by adjusting their position on the treadmill (Swarén et al., 2013). Two minutes after the end of the TT, BLa was measured. The test protocol was performed twice, once WR and once NR in a randomized and counter-balanced order, separated by 2–6 days.

In *Study II*, all participants started with the submaximal test NR. The submaximal test was performed as described in *Study I*, with the only difference being a lower increase in speed for every workload in *Study II* (0.42 $m \cdot s^{-1}$) (Figure 7). For testing WR, only two submaximal workloads were completed: the second workload from the submaximal NR protocol (women 2.36 $m \cdot s^{-1}$ and men 2.64 $m \cdot s^{-1}$) and

the workload closest to, but not above OBLA (4 mmol·L^{-1} of BLa) from the test NR. The incline and durations of the workloads were the same as for the submaximal test NR. After 7 min of active and passive recovery, participants commenced the same TT as described for *Study I*. Tests NR and WR were separated by at least 48 h and were performed before (pre) and after (post) the training intervention. During the training intervention, participants performed their normal training, with the only difference between groups being that IG aimed to carry their rifle during at least two additional training sessions·$week^{-1}$.

4.3.1.2 Measurements and equipment

In *Studies I* and *II*, all participants carried the same rifle with their own biathlon harness during testing (rifle mass 3.5 kg + harness ~ 0.2 kg). All roller-ski tests were carried out on a motor-driven treadmill (belt dimensions 3.3 × 2.5 m; Rodby Innovation AB, Vänge, Sweden). All participants used Pro-Ski S2 roller-skis (Sterners, Dala-Järna, Sweden) with a mean rolling resistance coefficient of 0.0216 or 0.0224 (determined as previously described by Ainegren et al., 2008) during testing. The roller-skis were pre-warmed for at least 60 min before testing to minimize the variation in rolling resistance (Ainegren et al., 2008).

Respiratory variables were measured throughout the submaximal and TT tests (AMIS 2001, model C, Innovision A/S, Odense, Denmark), with expired air sampled at 10-s intervals. Respiratory variables were calculated as the mean values for the last 30 s of the submaximal workloads or as the mean of the highest consecutive 30 s during the TT. The equipment was calibrated before each testing session using a calibration gas of 16% O_2 and 4.5% CO_2 (Air Liquide, Kungsängen, Sweden) and a 3-L syringe (Hans Rudolph, Kansas

City, Missouri, USA) at low, medium and high flow rates. HR was measured at 5-s intervals throughout the tests (Polar S810, Polar Electro Oy, Kempele, Finland). Between each submaximal workload and after the TT, fingertip blood samples were collected for the measurement of BLa (Biosen S_Line, EKF Diagnostics, Magdeburg, Germany) and RPE for breathing, arms and legs (Borg scale 6–20, Borg, 1970).

During the training intervention (*Study II*), all participants registered their training time, intensity and type of exercise in the Swedish Biathlon Federation's official online training diary (Maxpulse, Johan Bergman, Östersund, Sweden). When the participants trained WR, the session was manually marked in the diary. The training intensity was reported according to five training zones (defined as percentages of HR_{max}) and later divided into low-, moderate- or high-intensity training to correspond to previous literature (Seiler & Kjerland, 2006; Sylta et al., 2014b): A1 (60–75%, low), A2 (76–80%, moderate), A3- (81–85%, moderate), A3 (86–95%, high) and A3+ (> 95%, high). Strength training was reported as number of sessions and type (maximal, endurance or stability).

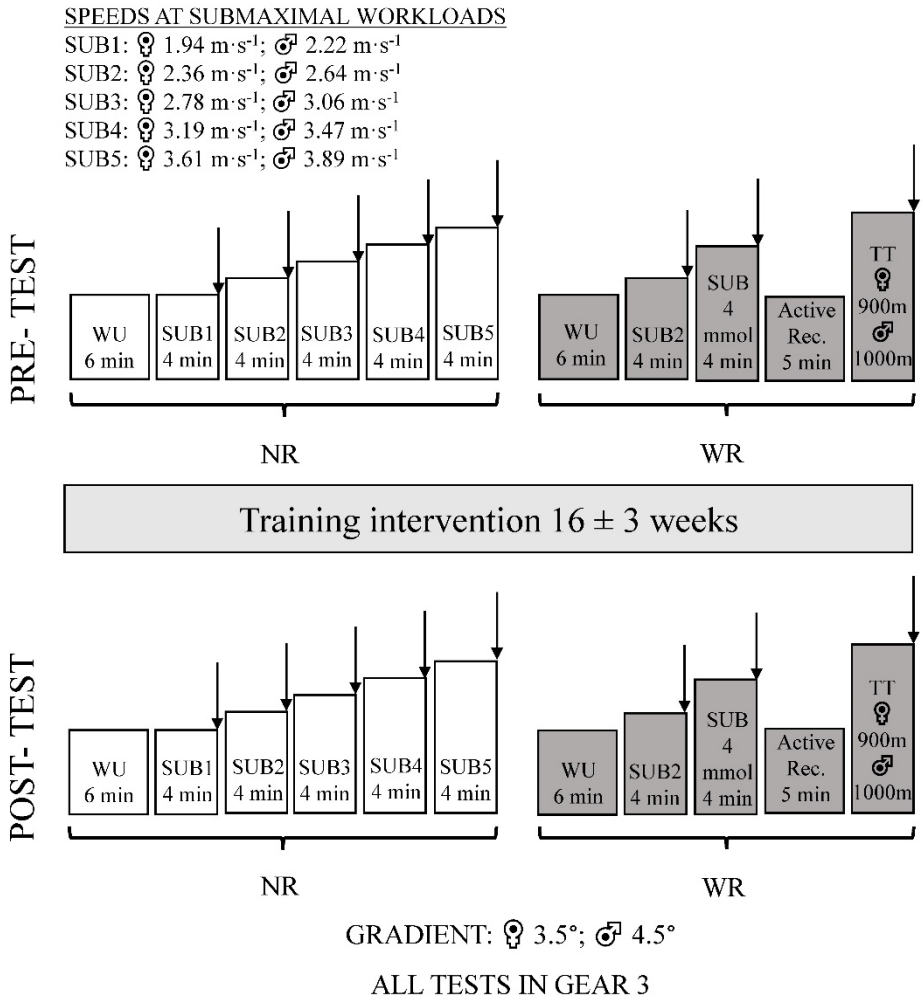

Figure 7. Schedule of the testing procedure before (pre) and after (post) the training intervention in Study II. The arrows indicate the measurements of blood lactate concentration and rating of perceived exertion. Respiratory variables and heart rate were measured throughout the test. WR = with rifle; NR = without rifle; WU = warm up; SUB = submaximal; TT = time trial; active rec. = active recovery; ♀ = women; ♂ = men.

4.3.2 Biomechanical testing (*Studies III–IV*)

4.3.2.1 Protocols

For *Study III*, the procedure of the $\dot{V}O_{2peak}$ tests are described by Stöggl et al. (2015), where the physiological results from these tests are presented. The experimental protocol during the second day of testing consisted of roller-skiing in two different gears (3 and 2), under two conditions (WR and NR, presented in a randomized and counter-balanced order) and at two different speeds (submaximal and simulated competition speeds) (Figure 8). All participants skied all workloads in gear 3 first (at an incline of 5°), followed by gear 2 (at an incline of 8°). The protocol started with a 10-min warm-up roller-skiing in gear 3 at ~ 60% of HR_{max}. The submaximal workloads lasted 5 min and speed was the same for all participants (gear 3: 2.22 $m \cdot s^{-1}$, gear 2: 1.67 $m \cdot s^{-1}$), while the simulated competition workload lasted 3 min and was individually calculated as 95% of the speed associated with $\dot{V}O_{2peak}$ for each gear.

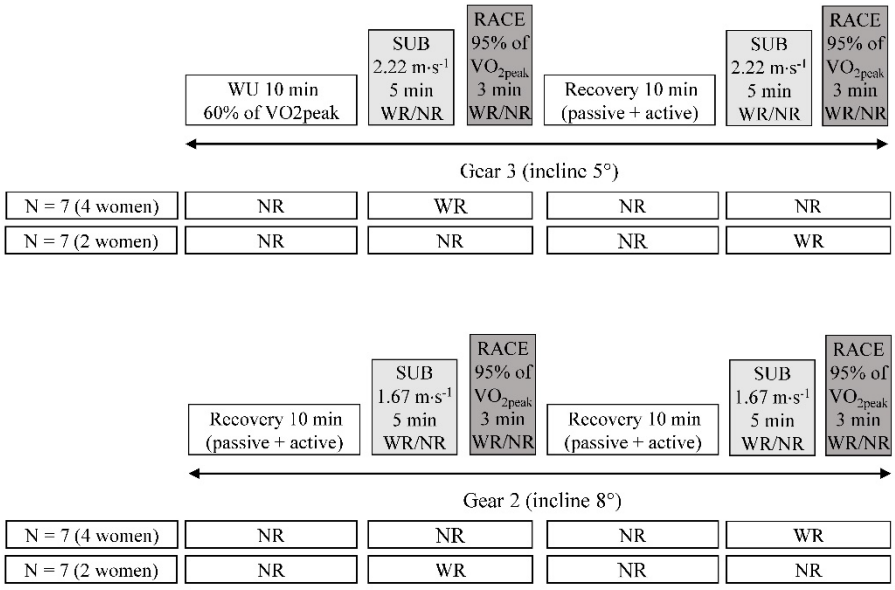

Figure 8. Schedule of the testing procedure for skiing with (WR) and without (NR) the rifle at submaximal (SUB) and simulated competition (RACE) speeds for skiing in gears 3 and 2. WU = warm up.

In *Study IV*, all tests were performed as on-snow skiing. The weather was stable for each participant but differed between testing days (the ambient temperature ranged between -14°C and +8°C). The participants skied the 2230-m long TT at competition speed twice, once WR and the other NR in a counter-balanced and randomized order. Before the TT, participants completed a standardised 15 min warm-up, which included familiarization of the course. Between the two TTs, participants performed 20 min of self-regulated active recovery and 10 min of passive rest. The skiing course was divided into discrete uphill (7 sections, 930 m in total), flat (3 sections, 500 m in total), and downhill (7 sections, 800 m in total) sections, with cut-off points at the highest or lowest point of altitude for the specific parts of the course (Figure 9).

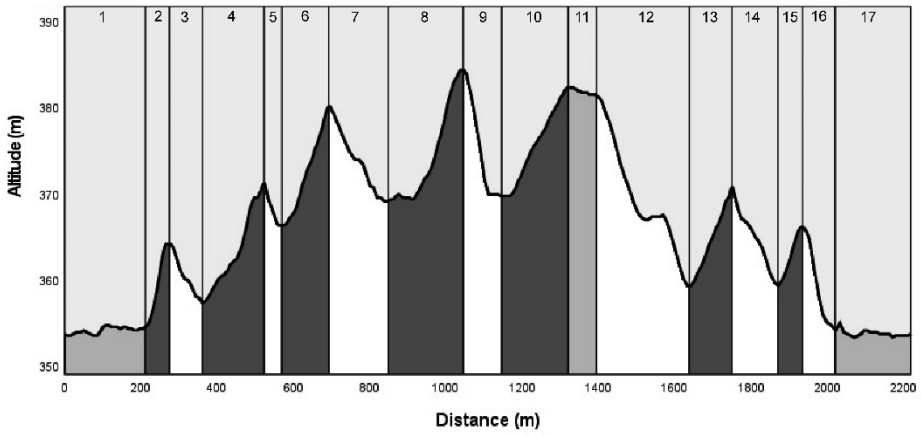

Figure 9. The topography of the 2230-m skiing course, which was skied twice. The course was divided into 17 sections according to terrain: 7 uphill (dark grey), 3 flat (light grey) and 7 downhill (white) sections.

4.3.2.2 Measurements and equipment

In both *Studies III* and *IV*, participants skied with their own biathlon rifle during WR. In *Study III*, all participants used the same pair of roller-skis (ProSki S2, Sterners, Nyhammar, Sweden; rolling resistance coefficient of 0.013), while the participants used their own on-snow skis in *Study IV*.

In *Study III*, kinematic 3D data for the whole body, poles, roller-skis and rifle were recorded with a Vicon MX13 motion capture system (Vicon Peak Ltd., Oxford, United Kingdom) during the last 30 s for all workloads (submaximal and simulated competition speeds WR and NR in gears 3 and 2). 33 reflective markers were placed over anatomical body landmarks according to a kinematic model (Plug-In-Gait, Vicon Peak, Ltd., Oxford, United Kingdom) and 15 additional reflective markers were placed on the rifle, poles, roller-skis and treadmill. The global coordinate system was right handed and defined as follows (treadmill incline set at 0°): (x) axis = sideways

across the treadmill (positive right); (y) axis = longitudinal axis of the treadmill (positive forward) and (z) axis = perpendicular to the ground (positive upwards). Six successive skiing cycles for each workload were used for analysis. Processing of all 3D data was performed using the Vicon Body Builder software (Nexus v 1.8.5, Vicon Peak Ltd., Oxford, United Kingdom).

In *Study IV*, participants were equipped with a portable 3D motion analysis system (MyoMotion, Noraxon Inc., Scotsdale, Arizona, USA) throughout testing. The system consisted of 12 inertial measurement units (IMUs) attached to the head, upper and lower spine, pelvis, left and right upper and lower arm, thigh and shank (for details see Staunton et al., 2022). Skiing speed was calculated from a global navigation satellite system (GNSS; Forerunner 920, Garmin, Olathe, Kansas, USA) as the change in position per time.

4.4 Calculations and data analysis

4.4.1 Physiological testing (*Studies I–II*)

4.4.1.1 Submaximal testing

In *Studies I* and *II*, respiratory variables ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and RER) and HR were calculated as the mean of the last 30 s of each submaximal workload and the highest consecutive 30 s values during the TT were reported as maximal values. Values for $\dot{V}O_2$ and RER were used to calculate gross energy expenditure (E_{gross}) for submaximal workloads 1–3. The speed at OBLA ($speed_{@4mmol}$) was calculated from the individual exponential relationship between BLa and speed during the submaximal workloads. PO was calculated as the power exerted to elevate the total mass (M_{tot}) against gravity and to overcome the rolling resistance according to the equation by Andersson et al. (2016):

$$PO\ (W) = M_{tot} \times g \times v(\sin(\alpha) + \mu_R \times \cos(\alpha)) \quad (1)$$

where M_{tot} = body mass (kg) and equipment (including the rifle for WR), g = gravitational acceleration ($m \cdot s^{-2}$), v = velocity ($m \cdot s^{-1}$), μ_R = rolling resistance coefficient and α = treadmill incline (°).

GE was calculated from the submaximal workload closest to, but not above RER = 1.00.

$$GE\ (\%) = (PO / MR_{ae}) \times 100 \quad (2)$$

The aerobic metabolic rate (MR_{ae}) was determined from the mean $\dot{V}O_2$ ($\dot{V}O_{2mean}$) and RER during the highest submaximal workload with a RER < 1.00 for skiing WR and NR according to Andersson et al. (2016):

$$MR_{ae}\ (W) = (E_{gross} \times 4184) / 60 \quad (3)$$

Where E_{gross} was given by:

$$E_{gross}\ (kcal \cdot min^{-1}) = (1.1 \times RER + 3.9) \times \dot{V}O_2\ (L \cdot min^{-1}) \quad (4)$$

4.4.1.2 Maximal testing

The total metabolic demand (MR_{demand}) for the TT was calculated using the GE method:

$$MR_{demand}\ (W) = PO_{TT}\ (W) / GE \quad (5)$$

where PO_{TT} was calculated using Equation (1) with the mean speed during the TT. The anaerobic metabolic rate (MR_{an}) was then calculated as:

$$MR_{an}\ (W) = MR_{demand} - MR_{ae} \quad (6)$$

where MR_{ae} was calculated as previously described in Equations (3) and (4) using the $\dot{V}O_{2mean}$ for the TT, assuming RER = 1.00.

MR_{an} was integrated over time for the TT and converted to an $\sum O_2$ deficit by multiplying by 0.047801 (i.e., a constant for the mL O_2 equivalent per joule) and assuming 100% carbohydrate utilization (Weir, 1949).

4.4.2 Biomechanical testing (*Studies III–IV*)

4.4.2.1 Determination of joint and equipment angles

In *Study III*, joint angles were measured as flexion/extension (i.e., rotation around (x)) for the thorax, shoulder, elbow, hip, knee and ankle, abduction/adduction (i.e., rotation around (y)) for the thorax, shoulder and hip, and internal/external rotation (i.e., rotation around (z)) for the thorax, shoulder and hip. The movements in the poles were measured as flexion/extension (rotation around (x)), and the roller-skis as abduction/adduction (rotation around (y)). The rotations around (x) and (y) in body joints and equipment are displayed in Figure 10. Due to the symmetrical nature of gear 3, data is presented as mean values for the left and right sides. For gear 2, the weight-bearing leg during PP was determined as the dominant side, and the other side as non-dominant. To evaluate the vertical height of the participant during roller-skiing, the vertical distance between the shoulder and treadmill was calculated ($vert_{dist}$). Maximal and minimal angles/values, as well as ROM (i.e., the difference between the maximal and minimal values) were calculated for all variables.

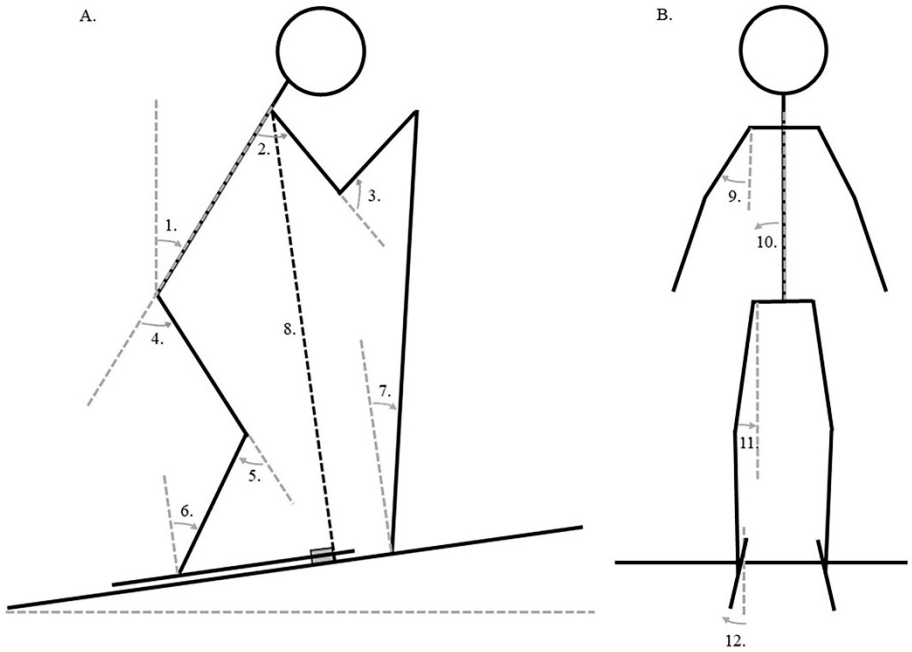

Figure 10. Joint and equipment angles for flexion/extension around (x) for (A) the thorax (1), shoulder (2), elbow (3), hip (4), knee (5), ankle (6) and pole (7), and abduction/adduction around (y) for (B) the shoulder (9), thorax (10), hip (11) and roller-ski (12). The dashed lines represent an angle of 0° and the arrow displays the positive direction of the movement. The dashed black line (8) in (A) determines the vertical distance between the shoulder and the treadmill.

4.4.2.2 Determination of gears used

In *Study IV*, the 3D projection of movement based on the IMU sensors was used to manually identify the gear used over the different types of terrain. Gears 2–4 were classified as previously described (Andersson et al., 2010; Nilsson et al., 2004) and as follows: gear 2, an asymmetric poling action for every second leg action; gear 3, a symmetric poling action for every leg action; gear 4, a symmetric poling action for every second leg action. All downhill skiing (gear 5 and skiing in the tuck position) was defined as skiing without pole propulsion (no poles, NP). Distance covered and time spent in the

different gears and the skiing speed were calculated for all 17 sections separately, for the different types of terrain (uphill, flat and downhill) and for the whole lap. Due to the importance of uphill skiing speed for overall performance (Andersson et al., 2010; Luchsinger et al., 2019b), the two longest uphill sections (sections 8 and 10, ~ 200 m per section) were analyzed further to assess the timing of the gear transitions.

4.5 Statistical analyses

All statistical analyses were processed using SPSS 24.0 Software (SPSS, Inc., Chicago, Illinois, USA) or IBM SPSS Statistics (version 27.0, IBM Corporation, New York, USA) with a level of significance set at $\alpha < 0.05$. For all four studies, variables were tested for normal distribution using the Shapiro-Wilks test of normality. Normally distributed data is presented as mean ± standard deviation (SD) and non-normally distributed variables as median and interquartile range (IQR). For normally distributed variables a two-way repeated-measures analysis of variance (ANOVA) (*Studies I* and *III* (WR/NR and different workloads/speeds/TT quarters)) or a two-way mixed ANOVA (*Study II* (within: pre-/post-test, and between: IG/CG); *Study IV* (within: WR/NR and between: women/men)) was used to investigate whether rifle, speed, sex and/or training intervention influenced physiological or biomechanical variables. For non-normally distributed variables or when sample sizes were small (e.g., when separating women and men) the non-parametric Mann-Whitney U test (between sex or IG/CG) or a Wilcoxon Signed rank test (between WR/NR or speeds) was used. For the ANOVA tests, effect sizes were calculated using partial Eta square (η^2_p) with the criteria (Cohen, 1988) 0.01 = small, 0.06 = moderate and 0.138 = large effect (*Studies II–IV*) or Cohens *D* with the criteria 0.2 = small, 0.5 =

moderate and 0.8 large effect (*Studies I* and *II*). Pearson correlation coefficients (r), or Spearman's Rho for smaller sample sizes, were used in *Studies I* and *IV* to investigate the linearity of the relationships between tested variables and TT performance, with the strength of the correlations interpreted as small (r = 0.10–0.29), moderate (r = 0.30–0.49) or large (r = 0.50–1.00) (Cohen, 1988). In addition, a multiple regression analysis was conducted in *Study I* to explain the degree of variance in TT performance attributable to the selected independent variables shown to be important for biathlon and XC skiing performance (i.e., $\dot{V}O_{2max}$, $speed_{@4mmol}$, MR_{an}, GE and muscle mass; for references, see section 1.4.1).

5 Results

5.1 Physiological effects of rifle carriage

5.1.1 Study I

5.1.1.1 Submaximal skiing

In *Study I*, each participant performed 3–5 submaximal workloads and data is presented for submaximal workloads 1–4 due to the low number of participants (n = 2) completing a fifth workload. The $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and E_{gross} were higher when skiing WR compared to NR for all submaximal workloads, while no differences between skiing WR and NR were found for HR or RER (Table 4). Breathing frequency was higher when skiing WR compared to NR at submaximal workloads 1 (36 *vs.* 34 breaths·min^{-1}, $p < 0.05$) and 4 (52 *vs.* 48 breaths·min^{-1}, $p < 0.05$), but no differences were observed for workloads 2 or 3 ($p > 0.05$). BLa was higher for skiing WR compared to NR during workload 4, but not during workloads 1–3 (Table 4). GE was higher when skiing WR compared to NR (16.7 ± 0.9 *vs.* 16.5 ± 1.1%, $p < 0.05$, Cohens *D* = 0.54), while the $speed_{@4mmol}$ was decreased while skiing WR (3.1 ± 0.4 *vs.* 3.3 ± 0.5 m·s^{-1}, $p < 0.05$, Cohens *D* = 0.35).

Table 4. Responses to skiing with (WR) and without (NR) the rifle during the first four submaximal workloads (Sub 1–4). Data are presented as mean ± SD.

	Sub 1 (n=17)		**Sub 2 (n=17)**		**Sub 3 (n=17)**		**Sub 4 (WR n=12, NR n=14)**	
	WR	**NR**	**WR**	**NR**	**WR**	**NR**	**WR**	**NR**
$\dot{V}O_2$ ($L \cdot min^{-1}$)	2.6 ± 0.5	2.5 ± 0.5*	3.1 ± 0.6	3.0 ± 0.6*	3.6 ± 0.7	3.5 ± 0.7*	4.0 ± 0.8	3.8 ± 0.7*
$\dot{V}CO_2$ ($L \cdot min^{-1}$)	2.4 ± 0.6	2.3 ± 0.5*	2.9 ± 0.6	2.8 ± 0.7*	3.6 ± 0.8	3.5 ± 0.7*	4.2 ± 0.9	4.0 ± 0.8*
$\dot{V}_E$ ($L \cdot min^{-1}$)	72.3 ±17.0	67.1 ± 16.4*	88.7 ± 19.9	82.5 ± 20.1*	112.5 ± 26.7	105.2 ± 24.6*	133.5 ± 31.3	122.2 ± 24.3*
HR ($beats \cdot min^{-1}$)	143 ± 14	143 ± 15	160 ± 16	159 ± 15	174 ± 14	173 ± 13	179 ± 11	179 ± 10
RER	0.91 ± 0.05	0.90 ± 0.05	0.94 ± 0.06	0.93 ± 0.05	1.00 ± 0.07	0.99 ± 0.07	1.05 ± 0.04	1.04 ± 0.05
BLa ($mmol \cdot L^{-1}$)	1.6 ± 1.1	1.7 ± 1.0	2.4 ± 1.7	2.4 ± 1.6	4.6 ± 2.6	4.1 ± 2.2	7.0 ± 1.2	6.1 ± 1.4*
E_{GROSS} ($kcal \cdot min^{-1}$)	12.7 ± 2.7	12.2 ± 2.5*	15.4 ± 2.9	14.7 ± 3.0*	17.9 ± 3.3	17.3 ± 3.3*	-	-

* = *Different from WR for the same submaximal workload, $P < 0.05$.*

$\dot{V}O_2$ = oxygen uptake; $\dot{V}CO_2$ = carbon dioxide production; $\dot{V}_E$ = ventilation rate; HR = heart rate; RER = respiratory exchange ratio; BLa = blood lactate concentration; E_{GROSS} = gross energy expenditure

5.1.1.2 Maximal skiing

Time to complete the fixed-distance TT was ~ 6.9% longer for skiing WR compared to NR (221.6 ± 21.6 *vs.* 207.3 ± 20.3 s, $p < 0.001$, Cohens $D = 1.52$). No differences were observed during the TT between skiing WR and NR for absolute $\dot{V}O_{2max}$, $\dot{V}_{Emax}$, HR_{max}, BLa_{max} or absolute MR_{ae}. For skiing WR, absolute and relative MR_{an} were lower compared to NR (absolute 27.5 ± 6.5 *vs.* 31.3 ± 8.0 kJ·min^{-1}; relative 26 ± 3 *vs.* 29 ± 5%; both $p < 0.01$, Cohens $D = 0.77$ and 0.80), and these differences were apparent during the first two quarters of the TT (Figure 11).

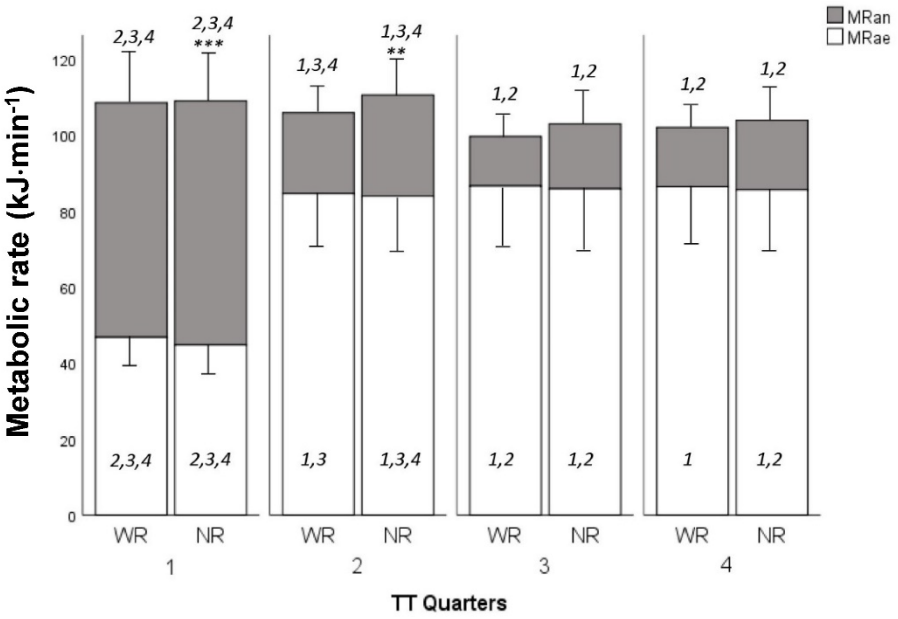

Figure 11. Aerobic (MR_{ae}) and anaerobic (MR_{an}) metabolic rates (kJ·min^{-1}) for each quarter of the maximal time trial (225 and 250 m per quarter for women and men, respectively) when skiing with (WR) and without the rifle (NR).
*** = different to NR, $p < 0.01$; *** = different to NR, $p < 0.001$. The numbers 1–4 indicate a difference from other quarters for the same condition (WR/NR), $p < 0.05$.*

TT performance for skiing WR was correlated with $speed_{@4mmol}$ ($r = 0.81$, $p < 0.001$), relative $\dot{V}O_{2max}$ ($r = 0.69$, $p < 0.01$) and MR_{an} ($r = 0.65$, p

< 0.01). The multiple regression analysis showed that $speed_{@4mmol}$ and MR_{an} together explained 84% (66% and 18%, respectively; $p < 0.01$) of the variation in TT skiing performance WR. When including absolute muscle mass, GE and $\dot{V}O_{2max}$ to this model, 91% of the variation in TT performance could be accounted for. When skiing NR, $speed_{@4mmol}$ and MR_{an} together explained 81% (43% and 38%, respectively; $p < 0.01$) of the variation in TT skiing performance NR. When including absolute muscle mass, GE and $\dot{V}O_{2max}$, the predictive value of the model increased to 88%.

5.1.2 Study II

5.1.2.1 Intervention period

Reported training data for the intervention period is presented in Table 5. The intervention period lasted 16.2 ± 3.4 and 15.8 ± 3.2 weeks for IG and CG, respectively ($p = 0.999$). IG trained more than CG during the intervention period (15.4 ± 1.4 *vs.* 11.2 ± 2.6 h·week^{-1}, $p < 0.001$) and reported fewer sick days (3.7 ± 3.0 *vs.* 11.4 ± 6.3 days in total, $p < 0.01$). All rifle carriage training was performed as roller-skiing in the skating technique, and IG carried the rifle more frequently and for longer time compared to CG (1.5 ± 0.6 *vs.* 0.6 ± 0.2 sessions·week^{-1} and 3.1 ± 0.6 *vs.* 1.1 ± 0.3 h·week^{-1}, both $p < 0.001$). Compared to CG, IG performed a lower proportion of the training at low intensity (82 ± 3 *vs.* 86 ± 2%, $p < 0.05$), more training at moderate intensity (11 ± 3 *vs.* 7 ± 3%, $p < 0.05$) and similar amounts of training at high intensity (7 ± 1 *vs.* 7 ± 2%, $p > 0.05$). The IG also performed more strength sessions each week compared to CG (1.9 ± 0.5 *vs.* 1.2 ± 0.6 sessions·week^{-1}, $p < 0.05$).

Table 5. Reported training duration (h) at low, moderate and high intensities, and in total for the intervention (IG; n = 10) and control (CG; n = 7) groups during the training intervention period lasting ~ 16 weeks.

	LOW INTENSITY		MODERATE INTENSITY		HIGH INTENSITY		TOTAL TRAINING		
	IG	CG	IG	CG	IG	CG	IG	CG	ES
Total training (h)	206.2±50.1	154.7±55.9	27.8±11.9	12.1±5.7**	17.8±6.4	12.1±3.8*	251.8±66.4	179.0±62.9*	0.49
RS skating (h)	68.8±17.1	53.3±20.0	17.9±7.2	7.3±3.5**	11.3±4.1	6.5±2.5*	98.0±27.0	67.1±24.0*	0.52
RS skating WR (h)	29.6±11.0	11.2±3.5***	12.9±4.8	1.6±1.4***	8.8±3.9	4.0±1.3**	51.3±18.7	16.8±5.3***	0.78
RS classic (h)	48.5±17.8	34.0±19.1	3.5±2.1	1.4±1.7	0.2±0.3	0.2±0.4	52.2±18.5	35.6±20.8	0.39
Running (h)	68.2±25.7	58.6±24.7	5.8±3.5	2.7±2.3	5.5±2.8	5.9±2.0	79.5±30.7	66.3±26.9	0.22
Cycling (h)	19.9±15.6	4.8±2.1*	0.1±0.2	-	0.2±0.3	0.2±0.5	20.2±15.9	5.0±2.2*	0.56
Other (h)	3.7±4.1	4.0±3.1	0.5±0.6	0.8±0.9	0.5±0.9	0.2±0.4	4.8±4.1	5.0±3.7	-0.03

*Different to IG: * = p < 0.05; ** = p < 0.01; *** = p < 0.001*

RS = roller-skiing; WR = with the rifle; ES = effect size (Cohens D)

5.1.2.2 Submaximal skiing

During submaximal skiing NR in *Study II*, the participants completed 3–6 workloads each. Only workloads 1–5 were analyzed, due to the low number of participants (n = 4, all in IG) completing workload 6. No differences were found between the IG and CG groups or pre- and post-tests for absolute $\dot{V}O_2$, HR (Figure 12A–B) or RER. The IG elicited a decreased BLa at submaximal workloads 2, 3 and 5 during post- compared to pre-testing, while no differences were observed for CG (Figure 12C). By contrast, the CG elicited an increased $speed_{@4mmol}$ during post- compared to pre-testing (3.31 ± 0.28 *vs.* 3.00 ± 0.28 $m \cdot s^{-1}$, $p < 0.05$, Cohens $D = 1.107$), while only a tendency for an increase was found for the IG (3.47 ± 0.14 *vs.* 3.25 ± 0.19 $m \cdot s^{-1}$, $p = 0.058$, Cohens $D = 1.318$).

For the two submaximal workloads WR, no differences were found between IG and CG or between pre- and post-tests for any of the measured variables (Figure 12D–F). No differences were found between IG and CG in response to the training (absolute or relative difference between pre- and post-tests) for any of the physiological variables measured during submaximal skiing WR or NR.

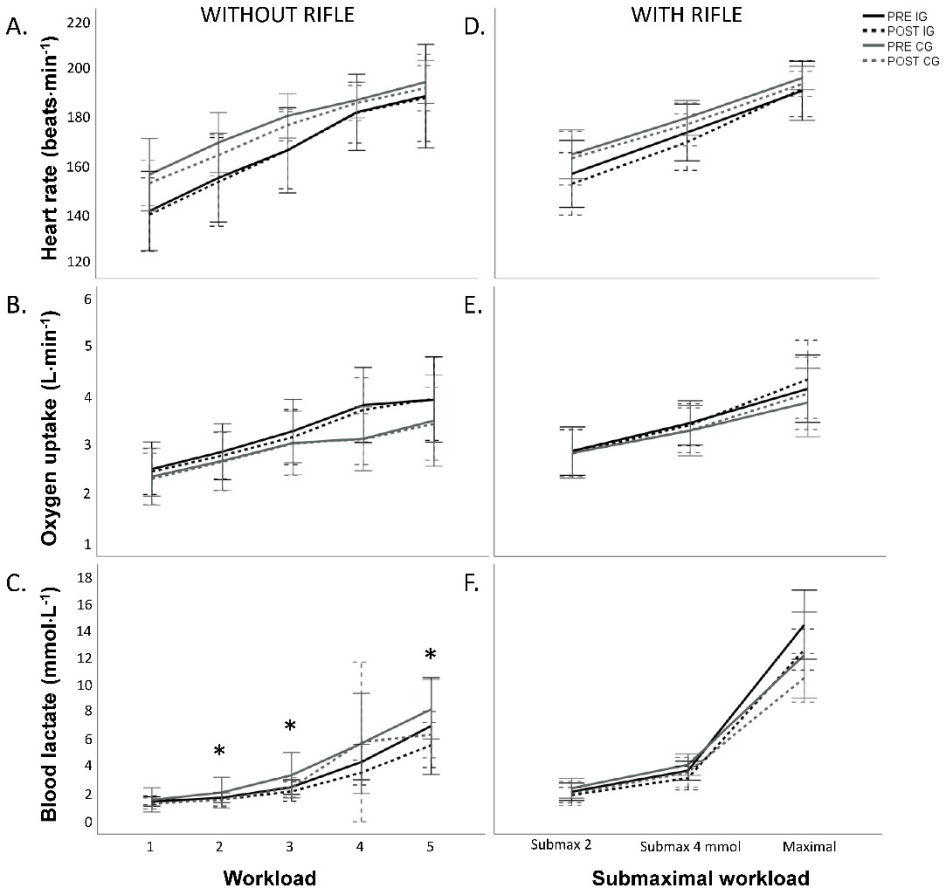

Figure 12. Physiological responses (mean ± SD) to submaximal roller-skiing without the rifle (A–C) and submaximal and maximal roller-skiing with the rifle (D–F) for heart rate (A, D), oxygen uptake (B, E) and blood lactate concentration (C, F), tested before (solid lines) and after (dotted lines) the training period for the intervention (IG; black lines) and control (CG; grey lines) groups.

** = significantly different from pre-test for IG, $p < 0.05$*

5.1.2.3 Maximal skiing

TT performance was superior for IG compared to CG (Table 6). $\dot{V}O_{2max}$ and MR_{ae} increased from pre- to post-testing, while maximal RER (RER_{max}) and BLa_{max} decreased (Table 6). No differences were found in the training responses between IG and CG (absolute or relative difference between pre- and post-tests) for any of the physiological or performance variables measured during the maximal TT.

5.1.3 Sex differences

In *Study I*, the mass of the rifle in relation to body mass was greater for the women compared to the men (5.6 ± 0.4 *vs.* 5.0 ± 0.4% of body mass, $p < 0.05$). However, there were no sex differences in the responses to rifle carriage for any of the measured variables during the submaximal workloads or the maximal TT (i.e., absolute or relative differences between WR and NR).

Table 6. Physiological responses (mean ± SD) to the maximal time trial when skiing with the rifle for the intervention and control groups measured before (pre) and after (post) the training period.

	Intervention Group		Control Group		Significant P value (ηp^2)		
	Pre	**Post**	**Pre**	**Post**	**Interaction**	**Group**	**Time**
Time (s)	210.1±15.9	205.3±18.2	230.9±9.2#	222.7±12.9#	NS (0.031)	0.015 (0.333)	0.017 (0.324)
Mean speed ($m \cdot s^{-1}$)	4.50±0.23	4.61±0.26	4.07±0.32#	4.22±0.33#	NS (0.016)	0.006 (0.404)	0.011 (0.356)
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	4.3±0.8	4.4±0.9*	3.9±0.8	4.1±0.8*	NS (0.008)	NS (0.051)	0.001 (0.574)
$\dot{V}O_{2max}$ ($mL \cdot kg \cdot min^{-1}$)	59.9±6.9	62.5±8.6*	56.7±8.4	59.4±8.8*	NS (0.001)	NS (0.039)	0.001 (0.575)
HR_{max} ($beats \cdot min^{-1}$)	191±11	191±10	197±5	194±6	NS (0.100)	NS (0.072)	NS (0.086)
RER_{max}	1.23±0.02	1.21±0.03*	1.19±0.05	1.17±0.04	NS (0.001)	0.012 (0.350)	0.009 (0.371)
BLa_{max} ($mmol \cdot L^{-1}$)	14.2±02.8	12.7±1.8*	12.2±3.5	10.6±1.9	NS (0.003)	NS (0.194)	0.026 (0.228)
Mean PO (W)	316±56	321±58	274±62	284±62	NS (0.027)	NS (0.113)	0.037 (0.258)
MR_{ae} (W)	1318±241	1366±275*	1213±226	1257±241*	NS (0.002)	NS (0.049)	0.002 (0.478)
MR_{an} (W)	514±112	502±106	427±113	423±81	NS (0.009)	NS (0.154)	NS (0.033)
$\sum O_2$ deficit ($mL \cdot kg^{-1}$)	72.4±12.5	69.3±10.9	68.1±14.5	65.4±9.0	NS (0.001)	NS (0.034)	NS (0.155)

** = Different from pre (for the same group), $p < 0.05$; # = different from IG (for the same test occasion), $p < 0.05$.*

$\dot{V}O_2$ = oxygen uptake; HR = heart rate; RER = respiratory equivalent ratio; BLa = blood lactate concentration; PO = power output; MR_{ae} = aerobic metabolic rate; MR_{an} = anaerobic metabolic rate; $\sum O_2$ deficit = accumulated oxygen deficit, NS = not significant.

5.2 Biomechanical effects of rifle carriage

5.2.1 Study III

5.2.1.1 Gear 3

There was no difference in ROM for $vert_{dist}$ between skiing WR and NR, but ROM increased at simulated competition speed compared to submaximal speed for WR and NR combined (0.22 ± 0.03 *vs.* 0.26 ± 0.04 m, $p = 0.001$, $\eta^2_p = 0.735$; Figure 13). The maximal values for $vert_{dist}$ were lower for WR compared to NR (1.53 ± 0.06 *vs.* 1.54 ± 0.06 m, $p = 0.001$, $\eta^2_p = 0.702$), without any difference in minimal values. When skiing WR, ROM was reduced in the thorax and shoulder (x), while the rotation around (y) and (z) was increased for the shoulders and elbow (x) compared to NR (Table 7). No differences were found in ROM between WR and NR for the lower body or equipment (roller-skis and poles). Compared to NR, skiing WR demonstrated less maximal extension in the thorax (x) (12.3 ± 4.2 *vs.* 10.2 ± 5.1°, $p < 0.01$, $\eta^2_p = 0.490$) and shoulders (x) (-27.4 ± 5.6 *vs.* -28.7 ± 6.4°, $p < 0.01$, $\eta^2_p = 0.443$), and greater maximal abduction (y) (68.7 ± 4.0 *vs.* 64.9 ± 5.5°, $p = 0.001$, $\eta^2_p = 0.687$) and external rotation (z) (-49.6 ± 10.8 *vs.* -44.5 ± 12.0°, $p = 0.001$, $\eta^2_p = 0.627$) in the shoulders. The sideward displacement of COM (x) decreased when skiing WR compared to NR (0.49 ± 0.06 *vs.* 0.50 ± 0.06 m, $p < 0.05$, $\eta^2_p = 0.390$) as well as the maximal and minimal vertical displacement (z) of COM (max: 1.26 ± 0.04 *vs.* 1.27 ± 0.04 m, $p < 0.001$, $\eta^2_p = 0.616$; min: 1.09 ± 0.05 *vs.* 1.10 ± 0.05 m, $p < 0.05$, $\eta^2_p = 0.335$). Skiing at simulated competition speed increased ROM in all measured variables in the equipment and upper and lower body, except for thorax rotation (z), compared to skiing at submaximal speed.

5.2.1.2 Gear 2

The ROM for $vert_{dist}$ was lower when skiing WR compared to NR (0.19 ± 0.04 *vs.* 0.20 ± 0.04 m, p = 0.001, η^2_p = 0.824) and at submaximal compared to simulated competition speeds (0.17 ± 0.03 *vs.* 0.21 ± 0.04 m, p = 0.001, η^2_p = 0.782; Figure 13). The maximal values for $vert_{dist}$ were decreased when skiing WR compared to NR (1.49 ± 0.06 *vs.* 1.51 ± 0.06 m, p = 0.001, η^2_p = 0.803), but there were no differences in minimal values.

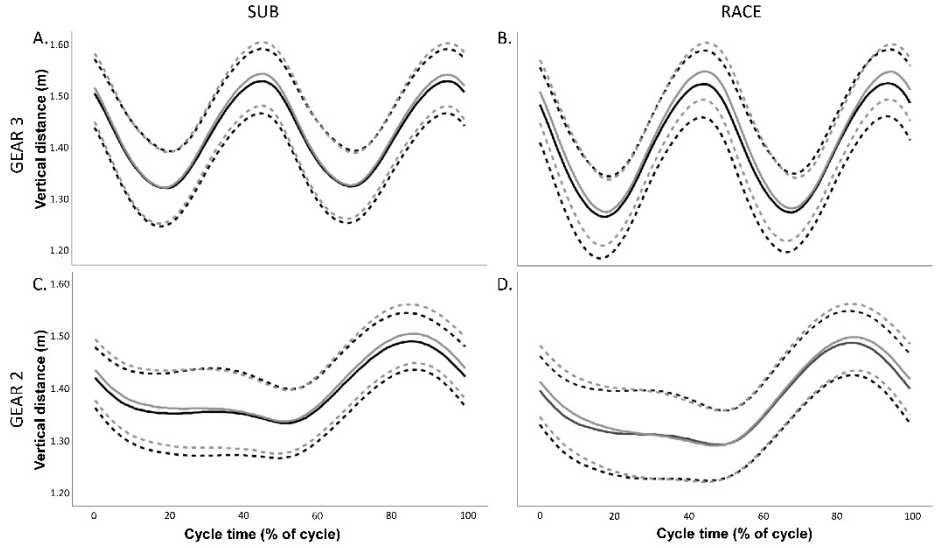

Figure 13. Normalized curves for the movement in vertical distance between the shoulders and treadmill during one cycle when roller-skiing in gear 3 (A–B) and gear 2 (C–D) with (black lines) and without (grey lines) the rifle at submaximal (SUB; A, C) and simulated competition speeds (RACE; B, D). The curves symbolize the mean (solid lines) ± SD (dotted lines).

When skiing WR, ROM was reduced in the thorax and shoulder (x), while the rotation around (y) for the thorax and non-dominant shoulder and (z) for the thorax and shoulder were increased compared to NR (Table 7). There were no differences between skiing

WR and NR for ROM in the lower body or equipment. Compared to NR, skiing WR demonstrated less maximal extension in the thorax (x) (14.4 ± 4.3 *vs.* 12.2 ± 4.8°, $p = 0.001$, $\eta^2_p = 0.702$) and shoulders (x) (dominant: -17.6 ± 6.5 *vs.* -19.3 ± 6.2°, $p < 0.05$, $\eta^2_p = 0.406$; non-dominant: -23.5 ± 8.6 *vs.* -26.3 ± 7.8, $p = 0.001$, $\eta^2_p = 0.680$), and greater maximal abduction (y) (dominant: 85.3 ± 8.0 *vs.* 82.6 ± 6.7°, $p < 0.01$, $\eta^2_p = 0.447$; non-dominant: 77.8 ± 9.9 *vs.* 74.0 ± 10.8, $p = 0.001$, $\eta^2_p = 0.593$) and external rotation (z) (dominant: -72.3 ± 11.1 *vs.* -68.3 ± 11.2°, $p = 0.001$, $\eta^2_p = 0.626$; non-dominant: -41.8 ± 8.9 vs. -38.5 ± 8.1, $p < 0.01$, $\eta^2_p = 0.443$) in the shoulders. The sideward displacement of COM (x) decreased when skiing WR compared to NR (0.30 ± 0.06 *vs.* 0.31 ± 0.05 m, $p < 0.001$, $\eta^2_p = 0.663$). Skiing at simulated competition speed increased ROM in all measured variables in the equipment and upper and lower body, except for the elbow (x) and hip (dominant (z); non-dominant (y), (z)), compared to skiing at submaximal speed.

Table 7. Range of motion for the upper body during roller-skiing with (WR) and without (NR) the rifle in gears 3 and 2 at submaximal (Sub) and simulated competition (Race) speeds. Data is presented as mean ± SD.

	WR		NR		ANOVA significant P value (ηp^2)		
	Sub	Race	Sub	Race	Interaction	Condition	Speed
Gear 3							
Thorax, x (°)	29.4 ± 4.7	32.3 ± 4.8*	30.9 ± 5.2#	34.0 ± 5.3#*	NS (0.001)	0.013 (0.391)	0.001 (0.823)
Thorax, y (°)	12.6 ± 3.4	14.0 ± 4.1	12.1 ± 3.4	13.8 ± 3.6*	NS (0.043)	NS (0.116)	0.015 (0.376)
Thorax, z (°)	12.9 ± 4.0	13.0 ± 4.3	12.4 ± 3.5	12.6 ± 4.1	NS (0.003)	NS (0.096)	NS (0.015)
Mean shoulder, x (°)	53.1 ± 7.7	61.2 ± 6.9*	54.4 ± 8.3#	62.6 ± 8.2*	NS (0.000)	0.006 (0.458)	0.001 (0.876)
Mean shoulder, y (°)	35.0 ± 3.6	39.9 ± 4.0*	31.9 ± 3.7#	36.4 ± 4.7#*	NS (0.022)	0.001 (0.592)	0.001 (0.782)
Mean shoulder, z (°)	76.3 ± 9.8	87.2 ± 12.1*	72.0 ± 9.2#	82.2 ± 11.5#*	NS (0.017)	0.003 (0.517)	0.001 (0.831)
Mean elbow, x (°)	56.1 ± 10.0	59.3 ± 9.3*	53.5 ± 10.1#	57.9 ± 8.4*	NS (0.087)	0.015 (0.376)	0.001 (0.585)
Gear 2							
Thorax, x (°)	23.7 ± 6.1	28.3 ± 4.5*	25.1 ± 6.2	29.7 ± 4.8#*	NS (0.000)	0.008 (0.429)	0.001 (0.753)
Thorax, y (°)	17.3 ± 3.0	20.3 ± 3.8*	16.4 ± 3.3	18.1 ± 2.5#*	NS (0.225)	0.008 (0.434)	0.001 (0.634)
Thorax, z (°)	27.1 ± 6.0	29.8 ± 6.9*	26.0 ± 5.1	29.1 ± 6.9*	NS (0.011)	0.026 (0.328)	0.003 (0.513)
D shoulder, x (°)	41.5 ± 11.4	45.8 ± 14.2*	44.8 ± 10.6#	48.8 ± 11.8*	NS (0.001)	0.007 (0.435)	0.005 (0.472)
D shoulder, y (°)	56.9 ± 12.6	60.0 ± 11.3*	54.2 ± 10.2	59.3 ± 10.8*	NS (0.127)	NS (0.129)	0.001 (0.639)
D shoulder, z (°)	90.1 ± 12.3	98.0 ± 14.3*	87.0 ± 12.6#	94.9 ± 14.8#*	NS (0.000)	0.010 (0.414)	0.001 (0.671)
D elbow, x (°)	65.4 ± 13.1	69.7 ± 10.9*	64.3 ± 12.9	69.8 ± 11.8*	NS (0.071)	NS (0.013)	0.001 (0.666)
N shoulder, x (°)	57.0 ± 10.2	56.1 ± 10.8	59.5 ± 11.1	60.1 ± 10.6#	NS (0.119)	0.004 (0.492)	NS (0.003)
N shoulder, y (°)	38.6 ± 6.6	42.6 ± 9.1*	35.2 ± 6.2#	39.0 ± 8.6#*	NS (0.003)	0.006 (0.452)	0.011 (0.405)
N shoulder, z (°)	63.1 ± 10.4	70.3 ± 10.8*	60.0 ± 9.3	65.5 ± 11.5#*	NS (0.131)	0.013 (0.391)	0.001 (0.558)
N elbow, x (°)	50.1 ± 9.6	51.8 ± 9.4	50.2 ± 10.0	51.0 ± 9.4	NS (0.046)	NS (0.049)	NS (0.084)

x = flexion/extension; y = abduction/adduction; z = internal/external rotation; D = dominant side; N = non-dominant side; ANOVA = analysis of variance; η^2_p = partial Eta square effect size, NS = not significant ($p \geq 0.05$).

** = significantly different from Sub for the same condition (WR/NR), $p < 0.05$; # = significantly different from WR for the same speed (Sub/Race), $p < 0.05$.*

5.2.2 *Study IV*

5.2.1.3 Time-trial performance

For skiing WR, time to complete the TT was increased compared to NR (median (IQR): 412 (90) *vs.* 395 (91) s, $p = 0.001$). However, when separating the course by terrain, there were no differences between skiing WR and NR in the time spent in uphill (242 ± 48 *vs.* 233 ± 53 s, $p > 0.05$, $\eta^2_p = 0.082$), flat (75 ± 9 *vs.* 73 ± 12 s, $p > 0.05$, $\eta^2_p = 0.098$) or downhill terrain (106 ± 7 *vs.* 104 ± 7 s, $p > 0.05$, $\eta^2_p = 0.120$). The distance covered and time spent in gear 2 was positively associated with TT skiing time (WR distance: $r = 0.649$, $p < 0.001$, time: $r = 0.901$, $p < 0.001$; NR distance $r = 0.516$, $p < 0.01$, time: $r = 0.755$, $p < 0.001$), while distance covered in gear 3 was negatively associated with performance for WR only ($r = -0.515$, $p < 0.001$).

5.2.1.4 Gear distribution

For the lap in total (Figure 14A, Table 8) and the uphill sections (Figure 14B), the biathletes covered more distance and spent more time in gear 2 and less in gear 3, when skiing WR compared to NR (uphill sections: gear 2 distance 322 ± 116 *vs.* 282 ± 113 m, $p < 0.001$, $\eta^2_p = 0.479$; time 107 (77) *vs.* 91 (78) s, $p < 0.05$; gear 3 distance 318 ± 106 *vs.* 358 ± 104 m, $p < 0.001$, $\eta^2_p = 0.384$; time 77 ± 26 *vs.* 84 ± 25 s, $p < 0.01$, $\eta^2_p = 0.276$). There were no differences between WR and NR for gear distribution during the flat sections (Figure 14C). For the downhill sections (Figure 14D) distance covered and time spent in gear 3 were less for skiing WR compared to NR (distance 90 ± 53 *vs.* 112 ± 71 m, $p < 0.05$, $\eta^2_p = 0.181$; time 16 ± 8 *vs.* 19 ± 11 s, $p < 0.05$, $\eta^2_p = 0.172$), while the time spent in gear 2 was longer (16 ± 9 *vs.* 13 ± 8 s, $p < 0.05$, $\eta^2_p = 0.221$).

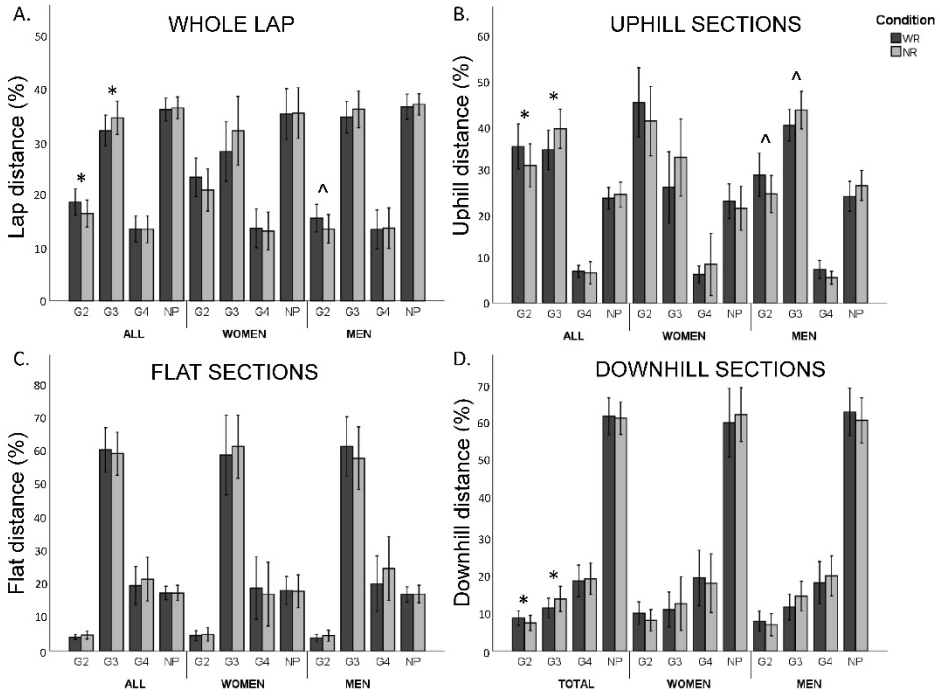

Figure 14. The distribution of gears 2–4 (G2–4) and skiing without pole propulsion (NP) when skiing with (WR) and without (NR) the rifle for the lap in total (A) and for the uphill (B), flat (C) and downhill (D) sections of the course.

** = significant effect of condition (women and men combined), $p < 0.05$*

^ = significant effect of sex (WR and NR combined), $p < 0.05$.

Table 8. The distribution of gears 2–4 and skiing without pole propulsion (NP) for the total 2230-m lap when skiing with (WR) and without (NR) the rifle. Normally distributed data are presented as mean ± SD and not-normally distributed data as median (IQR). For non-normally distributed variables, Wilcoxon Signed Rank and Mann-Whitney U tests were used instead of analysis of variance (ANOVA).

	All (n = 28)		Women (n = 11)		Men (n = 17)		ANOVA significant p value (η^2_p)		
	WR	NR	WR	NR	WR	NR	Interaction	Condition	Sex
Gear 2									
Distance (m)	413 ± 139	365 ± 142	512 ± 117	460 ± 125	349 ± 113	304 ± 120	NS (0.006)	0.001 (0.490)	0.001 (0.328)
Time (s)	133 (95)	113 (86)*	196 (69)	160 (57)*	97 (50)#	84 (45)*#	-	-	-
Speed ($m \cdot s^{-1}$)	3.05 ± 0.56	3.14 ± 0.63	2.58 ± 0.37	2.62 ± 0.39	3.35 ± 0.43	3.48 ± 0.52	NS (0.026)	NS (0.111)	0.001 (0.482)
Gear 3									
Distance (m)	713 ± 166	769 ± 182	620 ± 183	709 ± 216	773 ± 126	808 ± 151	NS (0.086)	0.001 (0.327)	0.049 (0.141)
Time (s)	141 ± 33	149 ± 37	138 ± 42	151 ± 46	143 ± 26	148 ± 30	NS (0.069)	0.008 (0.243)	NS (0.000)
Speed ($m \cdot s^{-1}$)	5.07 ± 0.73	5.19 ± 0.66	4.50 ± 0.57	4.69 ± 0.50	5.44 ± 0.56	5.51 ± 0.54	NS (0.038)	0.045 (0.146)	0.001 (0.421)
Gear 4									
Distance (m)	301 ± 141	300 ± 144	300 ± 117	290 ± 117	302 ± 158	307 ± 163	NS (0.005)	NS (0.001)	NS (0.001)
Time (s)	45 ± 20	44 ± 21	48 ± 17	47 ± 21	44 ± 22	42 ± 22	NS (0.001)	NS (0.006)	NS (0.011)
Speed ($m \cdot s^{-1}$)	6.60 ± 0.74	6.83 ± 0.78	6.31 ± 0.68	6.38 ± 0.77	6.79 ± 0.73	7.13 ± 0.65	NS (0.077)	0.031 (0.166)	0.024 (0.181)
NP									
Distance (m)	802 ± 131	810 ± 122	776 ± 162	781 ± 158	818 ± 108	829 ± 93	NS (0.002)	NS (0.016)	NS (0.034)
Time (s)	92 ± 18	91 ± 17	94 ± 23	91 ± 22	90 ± 12	90 ± 13	NS (0.019)	NS (0.021)	NS (0.004)
Speed ($m \cdot s^{-1}$)	8.81 ± 0.64	8.99 ± 0.60	8.36 ± 0.58	8.64 ± 0.68	9.10 ± 0.49	9.22 ± 0.43	NS (0.059)	0.005 (0.263)	0.002 (0.304)

η^2_p = partial Eta square effect size; NS = not significant ($p \geq 0.05$).

** = significantly different from WR, $p < 0.05$.*

 # = significantly different from women, $p < 0.05$.

The two longest uphill sections (section 8, mean incline 6.7° and section 10, mean incline 4.5°) were defined as steep ($STEEP_{up}$) and moderate (MOD_{up}), respectively, and analyzed in further detail. In the $STEEP_{up}$, the participants transitioned from gear 3 to gear 2 earlier when skiing WR, which resulted in less distance covered in gear 3 compared to NR (40 ± 18 *vs.* 51 ± 27 m, $p < 0.05$, $\eta^2_p = 0.174$; Figure 15). However, the distance covered using gear 2 was not significantly different between WR and NR. In the MOD_{up}, the transition from gear 3 to gear 2 also occurred earlier when skiing WR compared to NR, which resulted in more distance covered in gear 2 for WR (40 ± 48 *vs.* 25 ± 35 m, $p < 0.01$, $\eta^2_p = 0.304$), and less distance covered in gear 3 (84 ± 46 *vs.* 94 ± 35 m, $p < 0.05$, $\eta^2_p = 0.209$).

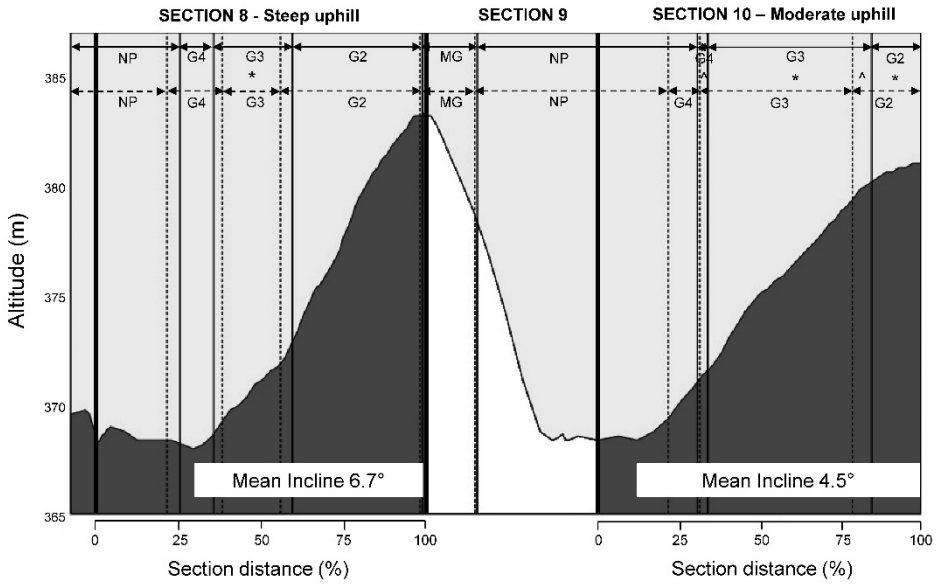

Figure 15. The distribution of gears 2–4 (G2-4) and skiing without pole propulsion (NP) when skiing with (WR, dotted lines) and without (NR, solid lines) the rifle in sections 8–10. The vertical lines show where the transition between gears occurred. Data is shown as mean values for the group in total.

MG = mixed gears

** = significantly different skiing distances for WR and NR for that gear, $p < 0.05$*

^ = significantly different transition duration between gears for WR and NR, $p < 0.05$.

5.2.2 Sex differences

5.2.2.1 Kinematics

When skiing in gear 3, the women demonstrated a smaller ROM for the poles (x) (WR: 49.8 ± 2.6 *vs.* 54.5 ± 3.6°; NR: 50.0 ± 2.7 *vs.* 54.4 ± 3.5°, both $p < 0.05$) and a larger ROM in the knee (x) (WR: 54.7 ± 6.3 *vs.* 48.0 ± 7.9°, $p < 0.05$) at simulated competition speed compared to the men. When skiing in gear 2, the only difference between sexes was a larger ROM in the non-dominant hip (x) for the women when skiing WR at submaximal speed compared to the men (62.3 ± 8.5 *vs.*

53.9 ± 4.5°, $p < 0.05$). The response to rifle carriage (i.e., difference between skiing WR and NR) was different between sexes for only one variable. When skiing at submaximal speed in gear 3, women demonstrated a larger difference between skiing WR and NR in the thorax (x) ROM compared to men (3.3 ± 2.1 *vs.* 0.3 ± 2.4°, $p < 0.05$). Maximal forward inclination of the thorax (x) during skiing in gear 3 WR at simulated competition speed was also negatively associated with body mass ($r = -0.666$, $p < 0.01$), but no significant correlations were found for skiing NR or at submaximal speed for WR. No sex differences in response to rifle carriage were observed for gear 2.

5.2.2.2 Gear distribution

Women used gear 2 to a greater extent than men over the total lap and during the uphill sections in terms of both distance and time, while distance covered but not time spent in gear 3 was less for the women compared to the men (Figure 14, Table 8). Performance time for the total lap was also slower for the women compared to the men (466 (56) *vs.* 373 (42) s, $p < 0.001$), and women demonstrated a lower skiing speed for all gears (Table 8). However, no interaction effects were found for WR/NR and sex for any of the tested variables, demonstrating that the effect of rifle carriage did not differ between sexes.

5.3 Summary of results

Rifle carriage affects physiological, biomechanical and performance aspects of biathlon skiing, and a summary of the results from *Studies I, III* and *IV* are illustrated in Figure 16.

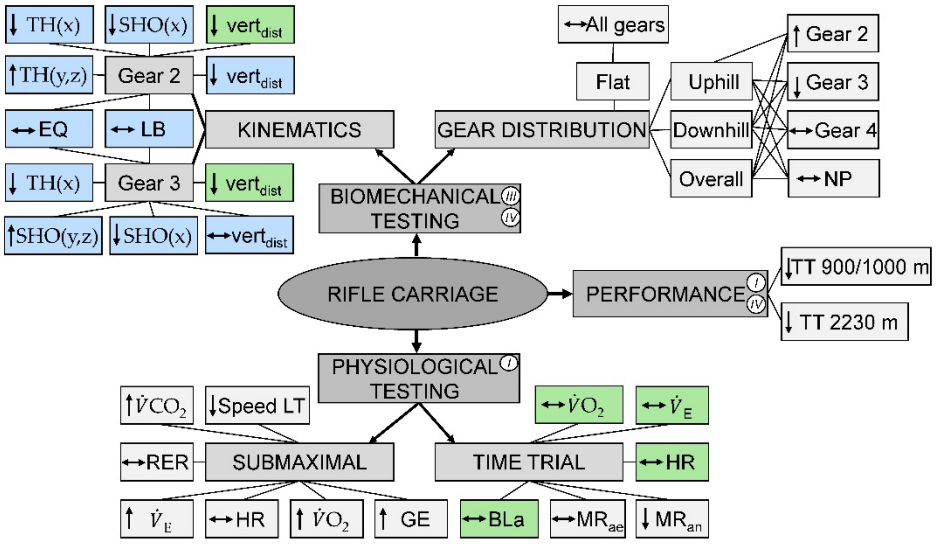

Figure 16. A summary of how rifle carriage affects biathlon skiing from physiological (Study I), biomechanical (Studies III–IV) and performance (Studies I and IV) perspectives. The blue boxes symbolize range of motion variables and the green boxes symbolize maximal values for the variable.
TH = thorax; SHO = shoulder; vert$_{dist}$ = vertical distance; EQ = equipment; LB = lower-body; (x) = flexion/extension; (y) = abduction/adduction; (z) = internal/external rotation; TT = time trial; $\dot{V}O_2$ = oxygen uptake; $\dot{V}CO_2$ = carbon dioxide production; $\dot{V}_E$ = ventilation rate; RER = respiratory equivalent ratio; HR = heart rate; LT = lactate threshold; GE = gross efficiency; BLa = blood lactate concentration; MR$_{ae}$ = aerobic metabolic rate; MR$_{an}$ = anaerobic metabolic rate; ↑ = an increase for WR vs. NR; ↓ = a decrease for WR vs. NR, ↔ = no difference between WR and NR.

The main results of the thesis are as follows:

1) Rifle carriage elicited an increase in respiratory responses and a decrease in $speed_{@4mmol}$ during submaximal roller-skiing, and a decrease in MR_{an} and performance during a maximal TT (*Study I*);
2) $Speed_{@4mmol}$ and MR_{an} together explained more than 80% of the variation in maximal TT performance (*Study I*);
3) One additional training session·$week^{-1}$ including rifle carriage did not affect physiological responses during submaximal or maximal roller-skiing, or biathlon skiing performance (*Study II*);
4) Rifle carriage elicited a decrease in the maximal $vert_{dist}$ during roller-skiing and a more forward lean in the thorax (*Study III*);
5) Rifle carriage altered the movements in the upper body, with decreased movements for flexion/extension and increased movements for abduction/adduction and internal/external rotation for the shoulder and thorax (*Study III*);
6) Rifle carriage elicited an increase in the distance covered and time spent in gear 2 and decreased the use of gear 3, where the use of gear 2 was negatively associated with skiing performance (*Study IV*);
7) Rifle carriage affected gear distribution to a greater extent in moderate compared to steep uphill terrain (*Study IV*);
8) Although the relative mass of the rifle was greater for female compared to male biathletes, the physiological and biomechanical responses to rifle carriage did not differ between sexes (*Studies I, III–IV*).

6 Discussion

The overall aim of this thesis was to investigate how rifle carriage in biathlon affects physiological and biomechanical variables related to skiing performance, as well as possible sex differences associated with rifle carriage. The results showed that rifle carriage elicits increases in respiratory responses during submaximal skiing, impairs performance and decreases MR_{an} and $speed_{@4mmol}$. Rifle carriage also results in a lower body position at PP, alters movements in the upper body and increases the use of gear 2. Even though the relative weight of the rifle was greater for the women compared to the men, responses to rifle carriage were similar for both sexes.

6.1 Physiological responses to rifle carriage

6.1.1 Submaximal skiing

Rifle carriage led to increases in metabolic and respiratory variables (E_{gross}, $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$) during submaximal roller-skiing compared to skiing NR (*Study I*), which is consistent with findings reported by Stöggl et al. (2015) and Rundell and Szmedra (1998). No differences in BLa were found between WR and NR at exercise intensities below the LT in the current study, suggesting that the aerobic energy system is able to meet the increased energy demands of rifle carriage, without increased involvement of the anaerobic energy system. The workloads were matched for skiing WR and NR, and BLa was higher when skiing WR compared to NR at the same absolute exercise intensity for workloads close to or above OBLA. This suggest that the aerobic energy pathways were no longer sufficient to meet the increased energy demands and BLa increased when skiing WR compared to NR, which reflects increased anaerobic energy metabolism. This is consistent with previous research, where

differences in BLa between WR and NR were demonstrated at absolute exercise intensities around or above the LT (Rundell & Szmedra, 1998; Stöggl et al., 2015), suggesting that the extra mass of the rifle has the largest impact at intensities near and above the LT. However, the inter-individual differences in BLa responses between skiing WR and NR were large in *Study I*, with some athletes demonstrating similar values for both conditions, while others demonstrated > 3 mmol·L^{-1} higher BLa for WR compared to NR for some submaximal workloads. Therefore, it may be beneficial to regularly monitor the differences in BLa responses when skiing WR and NR for each athlete and with that information, individualize rifle carriage training.

Borghols et al. (1978) estimated that each kg of external load carried increases the $\dot{V}O_2$ by ~ 33.5 mL·min^{-1} and $\dot{V}_E$ by ~ 0.6 L·min^{-1} during walking. Based on these estimates, the theoretical increases in *Study I* would have been ≥ 117 mL·min^{-1} for $\dot{V}O_2$ and ≥ 2.1 L·min^{-1} for $\dot{V}_E$ when carrying the biathlon rifle (which has a minimum mass of 3.5 kg). The actual increase in $\dot{V}O_2$ for skiing WR in *Study I* was ~ 100–200 mL·min^{-1} (3–5%), which is close to the estimation by Borghols et al. (1978), while the increase in $\dot{V}_E$ was ~ 5–15 L·min^{-1} (7–10%), which is much higher than predicted. The estimate may be affected by exercise intensity, since the relationship between $\dot{V}_E$ and the mass of the load is linear up to ~ 50% of $\dot{V}O_{2max}$ (Borghols et al., 1978), and/or the type of exercise performed (e.g., lower- or whole-body exercise).

The breathing frequency was significantly higher for skiing WR compared to NR at submaximal workloads 1 and 4 in *Study I*. This is in contrast to Stöggl et al. (2015), who observed no changes in breathing frequency, even though $\dot{V}_E$ was elevated when skiing WR. Previous research has shown that load carriage during walking or

running exercise affects the breathing pattern by increasing breathing frequency and/or reducing tidal volume compared to unloaded conditions (Armstrong et al., 2019; Larsson et al., 2022; Peoples et al., 2016; Phillips et al., 2016a; Phillips et al., 2016b). The reduced tidal volume is a result of the mass of the external load, but can also be affected by restriction of chest-wall expansion caused by the straps of the backpack (Dominelli et al., 2012; Peoples et al., 2016). Since the dead-space volume in the lungs is the same for every breath, a higher breathing frequency increases the total dead-space volume (Phillips et al., 2016b; Powers et al., 2021), meaning that a lower amount of the ventilated air reaches the alveoli where gas exchange occurs. The increase in breathing frequency can therefore lead to earlier fatigue of the respiratory muscles (Armstrong et al., 2019; Boffey et al., 2019; Phillips et al., 2016b). Faghy and Brown (2014) suggest that the threshold for inspiratory muscle fatigue is reduced during load carriage compared to unloaded conditions. Phillips et al. (2016b) also demonstrated that for short-duration exercise (< 10 min), the respiratory system can overcome the extra load and avoid compensatory alterations in breathing patterns (i.e., breathing frequency and tidal volume), but with prolonged exercise changes in breathing patterns are needed. The additional load of the rifle in biathlon during a relatively long competition time (20–50 min) may therefore increase breathing frequency due to decreased tidal volume, possible leading to respiratory muscle fatigue, which can have a negative impact on biathlon skiing performance. Taken together, the results of *Study I* support previous findings that rifle carriage in biathlon affects $\dot{V}_E$ during short-term (< 5 min) submaximal treadmill roller-skiing (Rundell & Szmedra, 1998; Stöggl et al., 2015), but it is still unclear how rifle carriage affects breathing

patterns during prolonged exercise, and whether eventual changes in breathing pattern has an effect on biathlon skiing performance.

During submaximal roller-skiing in *Study I*, no difference in HR was observed between WR and NR, despite the observed increases in metabolic and respiratory variables (E_{gross}, $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$) when skiing WR. However, biathletes often use HR to control and monitor exercise intensity during training, sometimes with the addition of BLa measurements. According to the results of *Study I*, HR and BLa (at lower intensities) do not seem to reflect the increased metabolic demands of rifle carriage, which is important to take into consideration when prescribing, analyzing and evaluating training loads for biathlon skiing WR or NR. It may also be beneficial to include other types of measurement to control intensity, such as RPE or accelerometers when training WR.

6.1.2 Maximal skiing

Study I is, to the author's knowledge, the first study to investigate how rifle carriage affects maximal roller-skiing performance and associated physiological variables. The study revealed that rifle carriage did not affect maximal respiratory variables ($\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$), which is partly supported by previous findings for load carriage in running (Fagundes et al., 2017; Peoples et al., 2016; Wang et al., 2021). However, other studies have demonstrated lower values for $\dot{V}_{Epeak}$ and $\dot{V}O_{2peak}$ during loaded compared to unloaded running (Larsson et al., 2022; Phillips et al., 2016a; Walker et al., 2015). One possible explanation for the contrasting findings is the difference in training status of the participants, where endurance-trained participants with higher $\dot{V}O_{2max}$ or $\dot{V}O_{2peak}$ values (> 60 mL·kg·min^{-1}) were included in the studies by Peoples et al. (2016) and Fagundes et al. (2017), as well as in *Study I*, compared to soldiers, university

students and healthy, active men ($\dot{V}O_{2max}$ ~ 50–55 mL·kg·min^{-1}) in the other studies (Larsson et al., 2022; Phillips et al., 2016a; Walker et al., 2015). Together these findings suggest that participants may need to be relatively well trained to be able to reach the same $\dot{V}O_{2peak}$ and $\dot{V}_{Epeak}$ values in loaded versus unloaded conditions.

Performance for the maximal TT was impaired by ~ 7% when skiing WR compared to NR in *Study I.* Speed$_{@4mmol}$ together with MR_{an} explained > 80% of the variation in maximal TT performance WR and NR, indicating that the anaerobic energy contribution is important for performance during a short (3–4 min) maximal TT. However, both speed$_{@4mmol}$ and MR_{an} were decreased when skiing WR compared to NR in *Study I*. Previous research has revealed that ~ 20–25% of the total energy during a XC skiing sprint (with a similar duration to the TT in *Study I*) is derived from anaerobic pathways (Andersson et al., 2017; Andersson et al., 2016; Losnegard et al., 2012; Losnegard et al., 2013; McGawley & Holmberg, 2014), with the greatest anaerobic contribution during uphill sections (Andersson et al., 2017; Andersson et al., 2019; Gløersen et al., 2020; Karlsson et al., 2018). Although the total anaerobic energy contribution in biathlon and XC skiing is relatively small, it still has a significant impact on skiing performance according to results from both *Study I* and previous research (Andersson et al., 2017; Losnegard et al., 2012). Reilly et al. (2009) have highlighted the importance of specificity in training programs to improve performance, with regards to energy systems, muscle groups and skill. As shown in *Study II*, biathletes only perform a small amount of rifle carriage training (CG: ~ 1.1 h·week^{-1}) and only a very small amount of this training (reported as time in HR zone A3+ or shorter sprints, < 10 s) stresses the anaerobic energy system, which may partly explain the difference in MR_{an} between

skiing WR and NR. However, the training performed in *Study II* was self-reported by the athletes in an online training diary divided into five different HR zones, which may have led to inaccuracies and/or discrepancies between athletes in how anaerobic training was reported. In competition, the differences in skiing times between biathletes are small (especially at the highest level) and an increased MR_{an} when skiing WR could have a positive impact on performance outcomes, since competitions may be decided during the last lap or final sprint of the competition.

6.2 Biomechanical responses to rifle carriage

6.2.1 Kinematics

The maximal $vert_{dist}$ was lower for roller-skiing WR compared to NR for gears 2 and 3 (*Study III*), which seems to be a result of a more forward lean of the thorax when skiing WR. This indicates that biathletes have a slightly less upright body position just before PP when skiing WR compared to NR. Research investigating the kinematics of the skating technique is limited, but upper-body work during gear 3 skiing is comparable to that performed during double poling in classical skiing (Sandbakk et al., 2015). Previous research has shown that during double poling, faster skiers demonstrate a higher vertical position of the COM (i.e., a more upright body position) (Zoppirolli et al., 2015), a greater forward body lean during PP and the first part of the poling phase (Jonsson et al., 2019; Zoppirolli et al., 2015), and more vertically positioned poles (Jonsson et al., 2019; Smith et al., 1996; Stöggl & Holmberg, 2011; Zoppirolli et al., 2015) compared to their slower counterparts. These results suggest that a higher overall body position at PP would allow the skier to use their body mass to a greater extent to generate higher forces through the poles during the poling phase. In practice, this

means that the lower body position WR during PP in *Study III* theoretically would have a negative impact on skiing performance.

The data presented by Stöggl et al. (2015) was collected on the same test occasions as for *Study III* and showed no differences between skiing WR and NR in peak or impulse pole forces, while increased peak leg forces were observed when skiing WR. The same study also demonstrated increased average cycle force when skiing WR compared to NR and this additional work (resulting from the additional mass of the rifle) appears to be produced by the legs (Stöggl et al., 2015). Hypothetically, this could be a result of the slightly lower upper-body position when skiing WR that prevents an increase in pole forces (peak and/or impulse of force). Previous research has shown that load carriage during walking or running exercise increases the work of the lower body and back due to a higher muscle activation and force production (Birrell et al., 2007; Brown et al., 2014; Paul et al., 2016; Quesada et al., 2000; Rice et al., 2017; Unnikrishnan et al., 2021; Walsh & Harrison, 2021; Walsh & Low, 2021). However, with only lower-body work (walking or running) performed in these studies, it still remains unclear how rifle carriage affects muscle activation during whole-body exercise, especially when taking the changes in body position caused by load carriage into consideration.

The results of *Study III* demonstrated that rifle carriage alters the movements in the upper body compared to roller-skiing NR in gears 2 and 3. When skiing WR, ROM in the thorax (x) was decreased, which was a result of the lower maximal thorax extension during WR compared to NR. A more forward tilt of the upper body and/or a decreased thorax (x) ROM has previously been found during load carriage (with absolute loads of 6–50 kg and relative loads of 20% of

body mass) in both running (Liew et al., 2020) and walking (Attwells et al., 2006; Brown et al., 2014; Harman et al., 2000; Krupenevich et al., 2015; Ling et al., 2004; Majumdar et al., 2010; Martin & Nelson, 1986; Morrison et al., 2019; Seay, 2015; Walsh & Low, 2021). Krupenevich et al. (2015) also showed a correlation between body mass and forward trunk lean during load carriage, suggesting that participants with a lower body mass are affected to a greater extent for a given absolute load. In addition, Keren et al. (1981) demonstrated that the breaking point where running becomes more efficient than walking for healthy men is at a lower speed for smaller compared to larger participants during load carriage with an absolute load weighing 20 kg. The mass of the rifle in biathlon is the same for all athletes (~ 3.5–4.0 kg), which may disadvantage biathletes with a lower body mass. This is supported by the findings from *Study III*, where body mass was negatively associated with maximal forward inclination of the thorax (x) when skiing WR in gear 3 at simulated competition speed. In addition to the changes in thorax (x) ROM, the movement in the shoulder (x) also decreased when skiing WR compared to NR (*Study III*). The decreased (x) ROM observed in *Study III* could be a result of the additional mass of the rifle itself, and/or due to the position of the biathlon harness holding the rifle, which may affect movements in the upper body.

Skiing WR decreased thorax and shoulder (x) ROM, but increased the ROM in shoulder abduction/adduction (y) and internal/external rotation (z), elbow (x) (gear 3) and the sideward tilt (y) and rotation (z) in the thorax (gear 2) (*Study III*). Rosén et al. (2019) showed that para-canoeists with impaired trunk function increased their shoulder ROM in all three directions (x, y, z) to compensate for the lack of movement and force production in the trunk compared to able-

bodied athletes. Speculatively, the increased ROM around (y) and (z) in *Study III* could be an attempt to compensate for the decreased ROM in the shoulder and thorax (x) caused by rifle carriage. However, ROM in the shoulder (x) during roller-skiing in gear 3 can be increased by training (Losnegard et al., 2017). More specifically, after six months of regular training (June to January), elite male XC skiers increased their ROM in the shoulder (x) and showed a tendency to increase hip (x) ROM, in addition to increased CT due to increased poling durations and a more forward body lean at PP (Losnegard et al., 2017). During the training period, skiing efficiency and performance improved, which was at least partly explained by the changes in skiing technique (Losnegard et al., 2017). Although the study by Losnegard et al. (2017) was performed with XC skiers (i.e., without rifle carriage), it still demonstrates the importance of an optimized skiing technique for skiing performance, which needs to be investigated further in biathlon.

When skiing in gear 2 and 3 in *Study III*, rifle carriage decreased the sideward displacement of COM (x) compared to NR, while the maximal and minimal vertical displacements of COM were lower in gear 3 for skiing WR. Previous research has shown that the postural body sway and vertical displacement of COM increases when standing or walking with a load (Bode et al., 2021; Strube et al., 2017) and changes in movement pattern (in body segments and/or COM) caused by load carriage probably increases the demand on the stabilizing muscles in the upper body compared to unloaded. Speculatively, an increased demand on the stabilizing muscles due to rifle carriage for relatively long durations (e.g., during a biathlon competition) may lead to a faster onset of fatigue compared to skiing NR. Previous research has shown that fatigue impairs the postural

balance and increases body sway in the standing shooting position (Bermejo et al., 2018; Ihalainen et al., 2018; Köykkä et al., 2021; Sadowska et al., 2019; Sattlecker et al., 2017) and postural balance is also related to shooting performance at rest and after high-intensity exercise (Ihalainen et al., 2018; Köykkä et al., 2021; Sattlecker et al., 2017). Since the final shooting bout is performed in the standing position in all competition formats, fatigue could have a crucial impact on biathlon shooting performance due to increases in body sway caused by rifle carriage. Taken together, changes in movement of the COM and upper body caused by rifle carriage (*Study III*) can possibly lead to a faster onset of fatigue in the stabilizing muscles, which may also affect standing shooting performance negatively. However, this needs to be investigated in future studies.

Rifle carriage in biathlon seems to affect only the upper body ROM, since no differences were found between WR and NR in the lower body or equipment ROM (*Study III*). Load carriage with heavier loads (15–55 kg or 10–40% of body mass) has been shown to increase peak hip flexion and hip (x) ROM during walking (Bode et al., 2021; Harman et al., 2000; Loverro et al., 2019; Majumdar et al., 2010; Middleton et al., 2022; Morrison et al., 2019; Seay, 2015; Silder et al., 2013; Sousa et al., 2022; Unnikrishnan et al., 2021; Vickery-Howe et al., 2021; Walsh & Low, 2021), probably as a result of a more forward tilt and/or less movement (x) of the pelvis (LaFiandra et al., 2003; Liew et al., 2020; Sousa et al., 2022). However, no differences in maximal or minimal angles or ROM in the knee or ankle (x) were found during XC roller-skiing with and without a weight vest (6% and 12% of body mass) in male XC skiers (Millet et al., 1998a), which is consistent with the results of *Study III*. Previous studies have shown increased peak hip adduction and/or (y) ROM in the hips

during walking with a load, which increases the step width, probably to maintain balance and stability (Birrell & Haslam, 2009; Loverro et al., 2019). However, this does not seem to be the case during biathlon skiing since no difference was found in movement rotation around (y) for the hips or roller-skis when roller-skiing WR and NR (*Study III*). Faster XC skiers have demonstrated smaller angles between the skis and the direction of movement when skiing in the skating technique (Zoppirolli et al., 2020), but this eventual relationship could not be tested in *Study III* due to the lack of performance-based tests.

In *Study III*, the participants performed roller-skiing at both submaximal and simulated competition speeds. The results showed that an increased speed enhances ROM in both the upper and lower body and equipment. This is in accordance with previous research in gear 3 demonstrating a greater hip and knee (x) ROM (Ohtonen et al., 2016) and double poling in the classic technique, which showed increased (x) ROM in the elbow, hip and knee with increased speed (Lindinger & Holmberg, 2011; Lindinger et al., 2009a; Lindinger et al., 2009b). Since skiing speed affects movements in the whole body and skiing WR alters the movement in the upper body (*Study III*), it may be beneficial to perform training at simulated competition speeds to improve the skating technique when skiing WR to improve biathlon skiing performance.

6.2.2 Gear distribution

In the literature, gear distribution is often counted as a biomechanical variable, although the choice of sub-technique is dependent on both physiological (e.g., muscle mass, body strength and aerobic capacity) and biomechanical factors (e.g., skiing technique). As described in section 1.5.1., several sub-techniques are used in biathlon competitions, and no data regarding gear distribution during on-

snow biathlon skiing or the effect of rifle carriage on the selection of sub-technique has been published in the scientific literature. According to the results of *Study IV*, when skiing WR biathletes used gear 2 to a greater extent and gear 3 to a lesser extent compared to skiing NR . This is consistent with previous research with male XC skiers, which demonstrated that an increased use of gear 2 was related to a decrease in overall skiing performance (Andersson et al., 2010). The most commonly used gear during XC skiing competitions for men is gear 3 followed by gear 2 (Andersson et al., 2010; Shang et al., 2022). During skiing in *Study IV*, ~ 37% and 40% of the course time was spent in gear 3 for WR and NR, respectively, which is consistent with the results of Andersson et al. (2010) and Shang et al. (2022). However, the use of gear 2 for the male biathletes in *Study IV* was somewhat higher (23–27% of the total course time) compared to 18% in the study by Andersson et al. (2010). This difference may be due to several factors, such as the physical capacity, performance level and/or age (~ 19 years in *Study IV vs.* ~ 26 years) of the participants, the topography of the course (~ 32 *vs.* ~ 18 m between the highest and lowest points) and/or skiing distance (2230 *vs.* 1425 m). The research regarding gear distribution during a whole lap of XC skiing is to the author's knowledge limited to two studies (Andersson et al., 2010; Shang et al., 2022), with neither of these studies including female skiers. The results of *Study IV* showed that the female biathletes used gear 3 for ~ 29% and 33% of the total lap time, while ~ 42% and 38% of the lap time was spent in gear 2 for WR and NR, respectively.

The difference in gear distribution between skiing WR and NR was greatest in uphill terrain (*Study IV)*. Due to the importance of uphill skiing speed for overall skiing performance (Andersson et al., 2010; Bolger et al., 2015; Shang et al., 2022), the two major uphills of the

course (section 8, $STEEP_{up}$ and section 10, MOD_{up}) were analyzed further. The differences in gear distribution and timing of gear transition (from gear 3 to gear 2) between WR and NR were more frequent in MOD_{up} (4.5°) compared to $STEEP_{up}$ (6.7°). In the $STEEP_{up}$, the incline was so steep that the biathletes started to ski in gear 2 at the beginning of the uphill even for NR, which could explain the lack of difference between WR and NR. This explanation is supported by Kvamme et al. (2005), who determined a range of inclines of 4.2–4.8° as the turn-over point where gear 2 becomes relatively more efficient to use (in terms of HR, $\dot{V}O_2$ and BLa) compared to gear 3 for male XC skiers. The same pattern was shown by Andersson et al. (2019), who compared two uphill sections with different inclines. For the slightly steeper terrain (4.2°) more XC skiers used gear 2 exclusively (mostly women), while for the less inclined uphill (3.7°) more men used gear 3 exclusively (Andersson et al., 2019), suggesting that the turn-over incline was between 3.7–4.2° for this specific population and conditions. During skiing in the MOD_{up} in *Study IV*, the additional mass of the rifle might have increased PO to the point where a change to a lower gear was needed (i.e., from gear 3 to gear 2). Therefore, rifle carriage may have a larger effect on gear distribution when skiing in moderate compared to steeper uphill terrains. However, the critical incline where a change in gear is necessary may depend on differences in physiological factors (e.g., training status and upper-body strength), technical ability, distance of the uphill, pacing strategies, course preparations and/or the friction between the ski and the snow (which is affected by the weather, ski waxing and choice of ski structure). The results of *Study IV* suggest that inclines where the transition between gear 3 and 2 normally occurs are more affected by the additional load of rifle carriage in biathlon compared to steeper uphill terrain. Speculatively, this turn-over point could be shifted by

developing physiological (e.g., upper-body mass and strength) and/or biomechanical factors (e.g., body position at PP, as shown in *Study III*), leading to greater use of gear 3 and thereby potentially improving biathlon skiing performance.

When the data in *Study IV* was divided into uphill, flat and downhill terrain, the gear distribution results revealed some anomalies. For example, during the uphill sections ~ 30 s in total was spent in NP, which is normally used in downhill terrain. By contrast, during the downhill sections gear 2 was used for ~ 60–70 s, and ~ 90–110 s was spent in gear 3, which are normally used in uphill terrain. When dividing the course into sections, the cut-off point was set at the highest or lowest point of the chosen part of the course. As shown in Figure 9, the course changed frequently from uphill to downhill. With this division of the track, participants often skied in the tuck position during the first part of the uphill sections, due to high speeds created and carried over from the previous section. For the downhills, the first part of the section consisted of skiing in gear 2 and/or 3, when the skiers worked to create as much speed as possible coming out of a previous uphill or flat section, before changing to the tuck position. This indicates that gear selection is somewhat delayed compared to the topography, which has also been seen for other physiological parameters, such as HR and $\dot{V}O_2$ (Bilodeau et al., 1991; Bolger et al., 2015; Born et al., 2017; Staunton et al., 2022).

6.3 Integrating physiology and biomechanics

The results of *Studies I* and *III* showed large differences between biathletes, with large SDs in relative and absolute differences between WR and NR in the physiological and biomechanical responses to rifle carriage. This suggests that individuals have

different ways to compensate for the additional mass of the rifle. Some biathletes demonstrated large differences in respiratory responses, BLa, ROM and/or body position between WR and NR, while others demonstrated similar values for the two conditions. However, different biathletes participated in *Studies I* and *III*, therefore it is difficult to conclude whether those with a smaller increase in physiological responses change their skiing technique to compensate for the rifle. The interactions between physiological and biomechanical responses to rifle carriage should be investigated further in future studies.

Using a competition-like TT in the field, *Study IV* demonstrated an ~ 4% higher skiing speed for NR compared to WR. The increased PO for skiing WR, together with physiological (e.g., respiratory responses, BLa and MR_{an}) and/or biomechanical (e.g., body position at PP and ROM) alterations due to rifle carriage affect the choice of sub-technique by forcing the biathlete to change to a lower gear during uphill skiing WR (*Study IV*), which may impair performance (Andersson et al., 2010; Shang et al., 2022). The individuals' response to rifle carriage may be affected by factors such as training status, experience of rifle carriage, body composition, anthropometrics, upper- and lower-body strength and skiing technique. Several of these factors are trainable, but to improve performance it may be beneficial to individualize training WR.

Performance in the on-snow TT in *Study IV* was impaired by ~ 4% when skiing WR compared to NR, while the difference between conditions during roller-skiing in the laboratory in *Study I* was larger (~ 7%). This difference in results may be accounted for by the different types of terrain and gears used in *Study IV*, compared to only uphill roller-skiing in gear 3 in *Study I*. Previous research has

shown that the greatest difference between faster and slower XC skiers is found in uphill terrain (Luchsinger et al., 2019b), which according to the results from *Study IV*, also seems to be the case for skiing WR and NR. In *Study IV* the biathletes skied ~ 9 s slower in the uphill sections WR compared to NR, while the mean difference for the total lap was ~ 13 s. Performing a TT in the field, including different terrains and sub-techniques, likely reflects a "real" competition better, compared to indoor TTs using one type of terrain/sub-technique. However, the response to rifle carriage seems to differ between individuals (*Studies I* and *III*) and to determine the specific effects of rifle carriage for each individual, laboratory tests that preferably combine physiological and biomechanical measurements, may be needed to individualize the training WR.

Even though the calculation of GE is based on physiological variables (i.e., $\dot{V}O_2$ and RER to calculate MR_{ae}), it is affected by both physiological (Cavanagh & Kram, 1985; Coyle et al., 1992; Donovan & Brooks, 1977; Powers et al., 1984) and biomechanical factors (Anderson, 1996; Sandbakk et al., 2010). Skiing WR increased GE compared to NR (*Study I*), while the maximal $vert_{dist}$ at PP and ROM in the shoulder and thorax (x) were decreased WR (*Study III*). The biomechanical changes caused by rifle carriage reported in *Study III* have previously been shown to be negatively associated with performance (Losnegard et al., 2017; Zoppirolli et al., 2020) and GE (Zoppirolli et al., 2015) in XC skiing. However, as stated previously, the participants were not the same in *Studies I* and *III*. For the biathletes in *Study III*, GE was unaltered by rifle carriage according to the results presented by Stöggl et al. (2015). It would therefore have been of interest to investigate whether the differences in GE observed in *Study I* were associated with changes in skiing technique.

Another factor to consider is the amplitude in the metabolic response to rifle carriage. The results of *Study I* demonstrated that the metabolic rate did not increase as much as the PO when skiing WR compared to NR. Previous research has shown that running with a load corresponding to 7% of body mass did not significantly increase the metabolic energy cost (mL O_2·kg body mass^{-1}·m^{-1}), but that running with a load weighing 15% of body mass did (Fagundes et al., 2017). Abe et al. (2011) also demonstrated that when including the mass of the load (~ 4% of body mass) into the calculation, running economy was improved. These results indicate that the increase in metabolic rate is not linear to the mass of the load when running with lighter loads. Due to this possible non-linear relation between metabolic rate and PO, the GE could increase when carrying lower loads, as shown in *Study I.* However, it would be of interest to investigate biomechanical effects of rifle carriage together with GE, to be able to draw better conclusions regarding the potential relationships between those factors.

6.4 Sex differences

All four studies in this body of work included both female and male participants, and in three of the studies one of the aims was to investigate possible sex differences associated with rifle carriage.

6.4.1 Physiological differences

Study I was the only study to measure body composition of the participants and the female biathletes had lower body and muscle mass, especially in the upper body, and higher absolute and relative fat mass compared to the male athletes. This is consistent with previous studies in XC skiing, where men had a higher muscle mass

compared to their female counterparts, with the largest differences in upper-body muscle mass (Hegge et al., 2016; Jones et al., 2021).

The results of *Study I* showed that the male participants had a higher absolute and relative $\dot{V}O_{2max}$, $\dot{V}_{Emax}$ and absolute MR_{ae} during the TT, and a higher absolute $\dot{V}O_2$ at OBLA. This is consistent with previous research demonstrating ~ 14–18% higher relative $\dot{V}O_{2max}$ values for male XC skiers and biathletes (Bolger et al., 2015; Jones et al., 2021; Laaksonen et al., 2020; Sandbakk et al., 2012b; Tønnessen et al., 2015) and a higher absolute $\dot{V}O_2$ at LT compared to women (Johansen et al., 2022; Jones et al., 2021; Laaksonen et al., 2020; Larsson et al., 2002; Sandbakk et al., 2012b). This difference in $\dot{V}O_{2max}$ is predominantly explained by the larger body size, muscle mass and total body hemoglobin in men (Calbet & Joyner, 2010; Hegge et al., 2016; Jones et al., 2021; Sandbakk et al., 2012b; Zelenkova et al., 2019).

Due to the lower body mass in the female participants, the relative mass of the rifle was greater for the women compared to the men in *Studies I–IV*. However, no sex differences in response to rifle carriage (i.e., absolute and relative differences between skiing WR and NR) were found for any of the measured physiological variables. Previous research has shown a greater difference in $\dot{V}_E$ and $\dot{V}O_2$ between WR and NR, and a trend for a higher BLa during submaximal roller-skiing among female biathletes compared to men (Rundell & Szmedra, 1998; Stöggl et al., 2015). However, the study by Rundell and Szmedra (1998) is more than 20 years old and during this time biathlon skiing speeds have increased markedly (Figure 3), partly due to changes in training regimes, but also because of improvements in skis, waxes and course preparations (Laaksonen et al., 2018a). Hansen et al. (2021) demonstrated that the differences in $\dot{V}O_2$ and PO between upper- and lower-body work were the same for female and male XC

skiers, which according to the authors indicate that female XC skiers have improved their strength and endurance in the upper body relative to men in the recent years. Speculatively, the reason that no difference in response to rifle carriage between men and women was observed in this thesis may be due to the small difference in the relative weight of the rifle between sexes (5.6–6.1% and 5.0–5.5% of body mass for women and men, respectively), the sample sizes of the studies, the variation in individual response to rifle carriage (as shown in *Studies I* and *III*) and/or changes in training regimes and upper-body strength/endurance, as previously demonstrated in female XC skiers (Hansen et al., 2021).

6.4.2 Kinematical differences

In *Study III*, the male biathletes demonstrated larger ROM in the poles (x) and smaller ROM in the knee (x) when skiing in gear 3 at competition speed compared to the women. This is in contrast to Bode et al. (2021), who demonstrated greater ROM in the knee (x) for men compared to women, even though the two sexes were matched for body mass and height, and this result was speculated to be due to differences in muscle mass between sexes. However, Bode et al. (2021) used treadmill walking and the female and male biathletes in *Study III* were not matched for body size, which may explain the different results between the studies. The only sex difference in response to rifle carriage in *Study III* was found for the thorax (x), where the female participants decreased ROM more when skiing WR compared to NR than the male participants. This is consistent with previous research on load carriage during walking, which has shown that women have a greater increase in forward trunk inclination (x) when loaded compared to their male counterparts (Krupenevich et

al., 2015; Martin & Nelson, 1986), which has also been shown to be related to the body mass of the load carrier (Krupenevich et al., 2015).

Previously published results from the same data collection as *Study III* demonstrated that the male participants generated higher pole forces compared to the women (Stöggl et al., 2015). Eventual sex differences in response to rifle carriage for the kinetic variables were not presented by Stöggl et al. (2015), although large differences in pole forces between sexes were observed with 50% higher peak and impulse of force for the male compared to the female biathletes. According to the results of *Study III*, rifle carriage increased the forward lean of the thorax more in the female biathletes, which may also affect the force production on the poles. This, together with the greater upper-body muscle mass in men (*Study I*), may at least partly explain the difference in pole forces between sexes.

6.4.3 Differences in gear distribution

Female biathletes used gear 2 to a greater extent than the men (*Study IV*), which is consistent with previous research (Andersson et al., 2019). In *Study IV*, no interaction effects were found for condition × sex for the lap in total, suggesting that rifle carriage affects the distance and time spent in different gears similarly for both sexes. The largest difference in skiing speed between the sexes was found in uphill terrain when gears 2 and 3 are normally used (*Study IV* and Bolger et al., 2015). As mentioned previously, the contribution from the upper body is larger for gear 3 compared to gear 2 (Millet et al., 1998c; Stöggl et al., 2015) and in relation to this, male XC skiers have demonstrated greater muscle masses in the upper body compared to their female counterparts (Hegge et al., 2016; Jones et al., 2021), which was also confirmed in *Study I*. The difference in muscle mass in the upper body between the sexes likely results in men creating higher

peak and impulse of pole forces during roller-skiing compared to women as shown by Stöggl et al. (2015), which probably impacts the use of gears 3 and 2. By increasing the strength and muscle mass in the upper body, especially for the female biathletes, the use of gear 3 may increase, which could lead to improved skiing performance.

6.5 Biathlon training

In *Study II*, the IG trained with the rifle for ~ 2 h·week^{-1} (~ 1 session·week^{-1}) more than the CG during the training intervention. The goal for the IG was to carry the rifle in at least two additional training sessions·week^{-1}, but this target was not fully reached (mean ± SD: 1.5 ± 0.6 sessions·week^{-1} for IG). After the ~ 16-week training intervention, no differences in training effects were found between the IG and CG. If the participants had completed the targeted amount of rifle carriage training, a difference between the groups might have been evident, although this is speculative. Previous research in the military setting has shown that one additional session·week^{-1} of load carriage training is enough to improve load carriage performance (walking or running) (Dicks et al., 2021; Knapik et al., 2012). Possible explanations for not observing the same effects in *Study II* might be the difference in the mass of the load carried (3.7 kg *vs.* 15–45 kg), differences in training status (well-trained athletes *vs.* moderately active participants), differences in training loads (11–15 *vs.* 3–10 h·week^{-1}) and/or the load carriage experience of the participants. Well-trained athletes that are used to load carriage with relatively low masses might need a greater stimulus to increase load carriage performance. The effects of a higher amount of additional rifle carriage training should be investigated in future studies. According to the results of *Studies I* and *III*, including training at intensities ≥ the LT and technique training WR may also be beneficial.

When combining training groups in *Study II,* improvements in TT performance, MR_{ae}, $\dot{V}O_{2max}$ (absolute and relative) and $speed_{@4mmol}$ were observed after the training period, while no change was found for the anaerobic energy contribution (i.e., MR_{an} or $\sum O_2$ deficit). This is partly in contrast to the findings of Losnegard et al. (2013) with XC skiers, which demonstrated an increase in performance and $\sum O_2$ deficit after 5 months of training, while $\dot{V}O_{2max}$ remained unchanged. A very small amount of high-intensity training, which stresses the anaerobic energy system, was performed WR in *Study II* and this may partly explain the lack of difference in anaerobic energy contribution during the TT after the training period when skiing WR. $Speed_{@4mmol}$ increased after the training period in *Study II* and, as shown in *Study I* and in previous research, speed and/or $\dot{V}O_2$ at the LT is an important factor for biathlon skiing performance (Laaksonen et al., 2020; Rundell, 1995; Rundell & Bacharach, 1995). Evertsen et al. (2001) showed that high-intensity training for 5 months increases the speed at LT for elite XC skiers, while training at moderate intensity did not. The duration of high-intensity training in *Study II* was much lower compared to the high-intensity group in the study by Evertsen et al. (2001) (~ 1–1.5 h·week^{-1} *vs.* ~ 10 h·week^{-1}), while the amount of high-intensity training was similar in *Study II* and the moderate-intensity group (Evertsen et al., 2001). Speculatively, this difference in training response may be due to differences between studies in physical capacity of the participants (elite *vs.* well-trained athletes), suggesting that elite athletes need a larger stimulus to increase speed at LT.

Due to limited time for testing, only two submaximal workloads were performed while skiing WR in *Study II*. The first workload when skiing WR was the same for all biathletes of the same sex

(submaximal workload 2 from the test NR), to allow comparisons in absolute values between athletes. The results of *Study I* and other previous studies have shown that rifle carriage only affects BLa at workloads close to, or above the LT (Rundell & Szmedra, 1998; Stöggl et al., 2015). Therefore, the second submaximal workload when skiing WR was individually set as the workload closest to but not above 4 mmol·L^{-1} of BLa when skiing NR. However, no differences in BLa were observed at the two submaximal workloads WR after the training intervention for IG or CG. This might be due the relatively large variation in performance levels (influenced by the inclusion of both men and women), too low intensities at the two workloads to detect any differences (i.e., slightly below 4 mmol·L^{-1} of BLa) or that the training stimulus was too low or not effective.

Study II is the first study to present the volume of load carriage training recorded by biathletes via an online training diary. Previous research has estimated rifle carriage training to be ~ 15–20% of the endurance-based training among elite biathletes (Laaksonen et al., 2018b), while the participants in *Study I* estimated that ~ 30% (~ 4 hours·week^{-1}) of the training was performed while carrying the rifle. *Study II* showed that only ~ 10% of the training was performed while carrying the rifle in the CG, which is lower than the estimated values in *Study I* and in the study by Laaksonen et al. (2018b). The training intervention was performed during pre-season (May–September/October) and the amount of rifle carriage may differ between training periods (e.g., the general preparation, specific preparation and competition phase) with higher amounts of training WR likely closer to the competition season. In biathlon, athletes start to compete WR at the age of 16 years, but the amount of rifle carriage training at younger ages is still unknown. Both the periodization of

rifle carriage training and the amount of training WR at different ages needs to be investigated further in future studies.

In *Study II*, nearly 40% of the total endurance-based training was performed as skate roller-skiing, with ~ 25% and 52% of the time roller-skiing executed WR for CG and IG, respectively. The precise effects of training depend on the patterns of motor unit recruitment, muscle fiber types engaged, types of muscle actions involved and energy systems used (Reilly et al., 2009). Nindl et al. (2016) also indicate the importance of load carriage training in the military setting, to recruit and activate the "right" muscles for the specific load carriage task. Therefore, previous research and the data from this thesis suggest that a high amount of the sport-specific training (i.e., skate skiing) should be performed WR to improve biathlon performance.

In *Study II*, the participants performed an average of 1.2–1.9 strength sessions·week^{-1} including maximal, stability and endurance strength training. Previous research has shown that a combination of endurance and strength training at least 3 times·week^{-1} for a minimum of 4 weeks improves load carriage performance in untrained and moderately-trained participants (Knapik et al., 2012). It seems to be particularly important to include upper- and/or whole-body strength training to improve walking or running performance with loads (Kraemer et al., 2001; Williams et al., 2002). Williams et al. (1999) showed that an endurance-based training program for British Army recruits improved aerobic fitness and 3.2-km load carriage performance (with 25 kg), but when including two whole-body strength sessions·week^{-1}, load carriage performance increased even further (3.6 *vs.* 8.9%) (Williams et al., 2002). Similar results were reported by Kraemer et al. (2001), where all groups performing

strength training improved load carriage performance but, the group performing purely endurance-based training did not. According to the authors, this may be a result of improved postural support after strength training. An improved postural support may also be of importance for standing shooting, since postural balance has been shown to be related to standing shooting performance (Ihalainen et al., 2018; Köykkä et al., 2021; Sattlecker et al., 2017). Previous research in XC skiing has shown that upper-body strength training, especially maximal strength training, can increase lean body mass in the upper body, double poling performance, double poling economy and/or peak pole forces (Castañeda-Babarro et al., 2022; Hoff et al., 2002; Hoff et al., 1999; Losnegard et al., 2011; Østerås et al., 2002). This might be even more important for biathlon skiing, where there is a greater demand on the upper body to carry and stabilize the additional mass. Speculatively, it may be beneficial to increase the amount of strength training sessions for biathletes, especially for the women, to improve skiing performance WR. Increased muscle strength can have a positive effect on the force production in the upper body (Østerås et al., 2002), thereby possibly increasing the use of gear 3 during skiing WR and improving the postural support of the trunk. This may have a positive effect on both skiing WR and standing shooting performance (Ihalainen et al., 2018; Köykkä et al., 2021).

7 Methodological considerations

The four studies included in this thesis contain a mixture of physiological (*Studies I* and *II*) and biomechanical (*Studies III* and *IV*) measurements performed during treadmill roller-skiing in the laboratory (*Studies I–III*) and on-snow skiing in the field (*Study IV*). Using a combination of explanatory (*Studies I, III* and *IV*) and exploratory studies (*Study II*) involving both mechanistic (*Studies I–III*) and more applied measurements (*Study IV*) permits both rigorous control (laboratory measurements) and high ecological validity (TTs and field measurements).

7.1 Physiological measurements

7.1.1 Calculations of GE

One benefit of GE, which was used as a measure of skiing efficiency in *Studies I* and *II*, is that the energy substrate used during exercise is also considered (compared to O_2 cost or economy, which only account for $\dot{V}O_2$). In the equation for PO during skiing, the total mass of the skier (including equipment) was used (Andersson et al., 2016), meaning that in *Studies I* and *II*, the mass of the rifle was also included in the total mass when skiing WR. GE was improved for skiing WR compared to NR, meaning that the PO increased more in relation to energy expenditure when skiing WR. When calculating GE without the mass of the rifle (i.e., the same total mass for WR and NR), the value for GE was lower when skiing WR compared to NR (15.9 ± 0.9 *vs.* $16.5 \pm 1.1\%$, $p < 0.001$). However, total work is increased when carrying a load, therefore the additional mass of the load should be included in the GE calculation.

7.1.2 Estimation of anaerobic metabolic rate

There are different ways of estimating MR_{an} and in *Studies I* and *II*, the GE method was used. As for the calculations of GE, the mass of the rifle was used in the estimation, although the differences in MR_{an} between skiing WR and NR persisted even when excluding the mass of the rifle from the calculations. The GE method has shown similar reliability as the maximal accumulated oxygen deficit (MAOD) method for estimating anaerobic energy contribution (Noordhof et al., 2011) and no significant differences in calculated anaerobic energy contribution between methods, even though clear within-individual differences existed (Noordhof et al., 2021). A benefit of the GE method is that data from only one submaximal workload in the physiological test is needed (Andersson & McGawley, 2018), which was favorable for testing WR in *Study II* since the testing time was limited. A limitation with the GE method is the assumption that GE is constant at submaximal and supramaximal intensities. GE has been shown to decrease during supramaximal cycling TTs (Noordhof et al., 2015), which may lead to an underestimation of the O_2 deficit. There are also different ways of calculating PO during a TT in skiing and previous research has shown that when acceleration is included in the equation, the estimated mean PO shows better agreement with performance time (Sundström et al., 2018) compared to the equation used in *Studies I–II* (i.e., using mean speed of the TT). However, in the study by Sundström et al. (2018) the participants roller-skied on a treadmill track simulation with inclines that varied between flat and uphill sections. Since the TTs in *Studies I* and *II* were completed at a fixed incline, the time spent accelerating/decelerating would have been less, which should decrease the differences between the two types of calculation. In addition, the participants in *Studies I* and *II* served as their own controls (comparing WR and NR) and therefore

choosing to use the PO equation probably had a minor effect on the results.

7.1.3 Online training diary

All biathletes connected to the Swedish Biathlon Federation (e.g., national teams, high schools and universities) use the same online training diary, which was also used for reporting the performed training in *Study II*. The participants were asked to manually mark the training sessions performed while carrying the rifle, meaning that the actual number of rifle carriage training sessions may be slightly higher or lower than reported. Even though all the biathletes use the same system for reporting their training, there may be discrepancies between individuals in how they count and report their training duration and time spent in different HR zones (e.g., whether they report their high-intensity training as time in the targeted HR zone or the total time of the high-intensity interval). However, previous research has shown that elite XC skiers demonstrate strong agreement between self-reported and measured training duration, while high-intensity training (time in HR zone) was slightly overestimated when self-reporting (Sylta et al., 2014a). On balance, the training diary used regularly by the biathletes recruited to participate in *Study II* was considered the best method for reporting and collecting training data.

7.1.4 Testing protocols

The test protocols used for skiing NR in *Studies I* and *II* were the same as those used for the athletes' normal roller-ski testing in the laboratory, which is typically performed 2–3 times·year^{-1}. This protocol was used to minimize the number of tests and laboratory visits for each biathlete and to limit the disturbance to their normal training plans. Gear 3 was used during all tests since this is the gear

used to the highest extent during XC skiing competitions (Andersson et al., 2010; Shang et al., 2022). The inclines and speeds of the submaximal workloads were chosen to suit biathletes at different performance levels and/or ages. This allows long-term testing using the same protocol, which makes it possible to follow the development of each individual and to make comparisons between different groups of biathletes. The treadmill incline was less steep for the women compared to the men (3.5° *vs.* 4.5°) and each submaximal speed was 0.28 $m \cdot s^{-1}$ slower. With these settings, the female biathletes could ski comfortably in gear 3 and perform the same number of submaximal workloads as the male biathletes. Due to the 10–15% higher competition skiing speeds in male biathletes and XC skiers (Andersson et al., 2019; Bolger et al., 2015; Luchsinger et al., 2018; Luchsinger et al., 2019a), the TT was shorter for the women (900 m) compared to the men (1000 m), to match the test durations as closely as possible.

7.2 Biomechanical measurements

7.2.1 Kinematical measurements

Measuring movements with 3D motion capture systems using reflective markers and multiple cameras is considered the gold standard for movement analysis (Springer & Yogev Seligmann, 2016). In *Study III*, a calibration process of the 3D motion capture system was carried out before each test according to the instructions of the manufacturer. In addition, all skiing workloads WR and NR were tested on the same occasion, meaning that the marker setup was completed only once for each participant, which minimizes the error due to placement of the markers. For the kinematical analysis, only maximal and minimal values (angle or distance) and ROM were used. Since no previous study has investigated how rifle carriage

affects biathlon skiing, this was considered as a logical first step. Therefore, the data presented in *Study III* did not investigate the movements (i.e., "shape of the curve") between the maximal and minimal values or angular velocities for skiing WR and NR. This may be investigated in future studies, for example using statistical parametric mapping.

7.2.2 Selection of gears used

In *Study IV*, the participants wore a portable 3D motion system consisting of IMUs while skiing. The software produced a 3D projection of movement based on the sensor data and the gears were identified manually as gears 2–4 and skiing NP. Previous studies have used five or six different gears (also divided into gear 5, curves and/or tuck skiing) (Andersson et al., 2010; Shang et al., 2022), which is different to the analyses used in *Study IV*. The selection of gears in *Study IV* was made due to the lack of reference points from the course (e.g., smaller bumps, curves or transitions) from the 3D projection. It was sometimes difficult to classify the sub-techniques in downhill terrain as gear 5, smaller curves or just corrections of foot position to increase stability, and therefore all skiing without pole propulsion was defined as NP. Since the only differences between skiing WR and NR were found for the lower gears (2 and 3), the selection of sub-techniques used in *Study IV* should have been sufficient for answering the specific research question.

7.3 Laboratory- vs. field-based skiing

In the present thesis, *Studies I–III* were performed as roller-skiing in a laboratory setting while *Study IV* was performed as on-snow skiing. Good ecological validity has been shown between treadmill roller-skiing and on-snow skiing performance (Laaksonen et al., 2020).

However, on-snow skiing has been shown to increase CT and pole push times slightly during skiing in gear 3, and elicit a wider sideways hip range of displacement compared to roller-skiing (Myklebust et al., 2022). There are also some additional factors that potentially differentiate these two types of skiing modes. When roller-skiing, the contact area between the ground (treadmill or asphalt) and the roller-ski wheels is much smaller compared to the contact area between snow and regular skis. This may result in a reduced effect of pressure distribution on resistance during roller-skiing. Previous research has shown that during on-snow skiing, slower skiers exert more pressure through the medial part of the foot compared to faster skiers (Pavailler et al., 2020). An increased medial pressure during on-snow skiing in the skating technique is negatively correlated to gliding time (Pavailler et al., 2020), which in previous research has also been shown to be negatively related to performance (Stöggl et al., 2011). The pressure on the medial part of the foot also seems to increase during skiing WR compared to NR in young female biathletes (Jonsson & Laaksonen, 2015), suggesting that a change in the distribution of pressure may have an even larger impact during biathlon on-snow skiing. Taken together, a more even distribution of pressure in the mediolateral dimension during on-snow skiing may increase the gliding time, due to decreased friction between the ski and snow. Therefore, on-snow skiing might be more sensitive to biomechanical alterations compared to roller-skiing, and the difference may be even larger during skiing WR compared to NR.

The distribution of pressure seems to affect the coefficient of friction between the snow and ski, as do changes in snow type, surface of the ski or snow temperature (Buhl et al., 2001; Saibene et al., 1989), with the highest skiing speeds at snow temperatures of ~ -3°C (Buhl et al.,

2001). Changes in rolling resistance due to differences in temperature have also been shown for indoor roller-skiing, where a 30-min warm-up of roller-skis decreased the rolling resistance to ~ 60–65% of its initial value (Ainegren et al., 2008). Increased rolling resistance has also been shown to affect physiological (e.g., increased $\dot{V}O_2$, HR and BLa) (Ainegren et al., 2009; Hoffman et al., 1998; Millet et al., 1998b) and biomechanical factors (e.g., increased CR and poling forces) (Millet et al., 1998b) during submaximal roller-skiing. Thus, to minimize the change in rolling resistance during testing, the roller-skis were pre-heated for 30–60 min before testing in *Studies I–III*. Previous research has also shown that for on-snow skiing the coefficient of friction decreases with increased load (i.e., total mass) at snow temperatures below -6°C (Buhl et al., 2001), suggesting that rifle carriage (which increases the total mass) may lower the friction in colder weather compared to skiing NR. In contrast, rolling resistance seems to increase with load during roller-skiing (Ainegren et al., 2008), meaning that the additional mass of the rifle may affect the coefficient of friction/rolling resistance differently for on-snow skiing and roller-skiing. In summary, due to the differences in friction/resistance and sensitivity to force distribution between roller-skiing and on-snow skiing, the translation of results between skiing modes must be made with some caution.

Due to the effect of snow temperature on the coefficient of friction during on-snow skiing, a limitation of *Study IV* is the variation in weather conditions between the testing days. The air temperatures ranged from -14°C to +8°C, which likely changed the coefficient of friction between the testing days and thereby also skiing performance (i.e., skiing speed) (Ainegren et al., 2009). While within-participant conditions were standardized (i.e., the WR and NR tests were

conducted on the same day and were separated by just 30 min), the comparison between sexes and overall group results regarding gear distribution could be affected by the weather conditions, as gear choices are affected by skiing speed (Kvamme et al., 2005). The mean air temperature for the women was -2.3 ± 4.1°C, while the mean temperature for the men was -0.5 ± 5.9°C ($p > 0.05$), with 33% and 47% of the participants tested in temperatures above 0°C for women and men, respectively.

7.4 Small sample sizes and elite performance

One challenge when studying well-trained and elite athletes (tier 3–5 according to McKay et al., 2022) is the number of participants available for research. In the Swedish Summer Biathlon Championships (i.e., roller-skiing) in 2022, ~ 40 women and 40 men participated (from age 18 years upwards) in the sprint competition, while slightly more biathletes participated in the Swedish Winter Biathlon Championships (i.e., on snow) in the sprint competition (48 women and 47 men). There is large variation in performance between these biathletes, with the mean skiing speeds ranging between 4.15–6.99 $m \cdot s^{-1}$ for the women and 5.90–7.65 $m \cdot s^{-1}$ for the men in the summer sprint competition (the races includes the winner of the senior class and the last placed athlete in the youngest class, 18–19 years). These biathletes live all over Sweden, with different opportunities and goals for the sport. In the four studies of the present thesis, the number of participants varied between 14–28 and included both women and men. The mean skiing speeds for the TTs WR in *Studies I* and *IV* ranged between 3.69–4.56 and 3.48–5.17 $m \cdot s^{-1}$ for the women and 3.57–4.75 and 5.01–6.74 $m \cdot s^{-1}$ for the men, respectively. With a relatively low number of participants and large

variation in performance levels, it can be a challenge to detect statistical differences and correlations.

Large training effects or improvements in performance are seldom observed among well-trained athletes. However, a small increase may be of the greatest importance. The relevance of small differences in elite sports can lead to a mismatch between required and achievable sample sizes, which increases the risk of failing to detect an effect of relevant magnitude (Skorski & Hecksteden, 2021). A small sample size can be strengthened by a high reliability of measurement tools, standardization of testing protocols and timing of the test, an increased number of data-points, the use of control groups and randomization (Hecksteden et al., 2022; Skorski & Hecksteden, 2021). In *Studies I, III* and *IV*, the participants served as their own controls when investigating the effect of rifle carriage on biathlon skiing, which was always tested in a randomized order. However, there may still be responses to rifle carriage that were not detected in *Studies I–IV* due to low sample sizes, large variation between participants' performance levels (which is also influenced by sex) and relatively small changes between WR and NR conditions.

8 Conclusions

The overall aim of this body of work was to investigate how rifle carriage in biathlon affects physiological and biomechanical variables related to skiing performance, as well as possible sex differences associated with rifle carriage. During submaximal skiing, rifle carriage increased the respiratory responses ($\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$), without eliciting any differences in HR *(Study I).* When skiing WR, BLa increased at workloads close to or above the LT and the $speed_{@4mmol}$ decreased compared to NR *(Study I).* Rifle carriage also decreased TT performance during both treadmill roller-skiing in the laboratory (*Study I*) and on-snow skiing in the field (*Study IV*). During maximal treadmill roller-skiing the MR_{an} decreased when skiing WR compared to NR, and MR_{an} together with $speed_{@4mmol}$ explained ~ 80% of the variation in TT performance WR (*Study I*). From a biomechanical perspective, rifle carriage altered the ROM in the upper body (thorax and shoulder), with decreased movements in (x) and increased ROM in (y) and (z) (*Study III*). When skiing WR, the biathletes decreased the maximal height of their shoulders, which was explained by a more forward lean of the thorax compared to skiing NR (*Study III*). On-snow skiing WR increased the use of gear 2 in comparison to NR, while the distance covered and time spent in gear 3 decreased (*Study IV*). Rifle carriage seems to have a larger impact on gear distribution during moderate (~ 4.5°) compared to steep (~ 6.7°) uphill terrain, where changes between gears 3 and 2 were more frequent (*Study IV*).

The female biathletes in these studies demonstrated lower body masses (*Study I–III*), muscle masses (especially in the upper body) (*Study I*), $\dot{V}O_{2max}$ (*Study I*), $\dot{V}_{Emax}$ (*Study I*) and use of gear 3 (*Study IV*)

compared to the men. Although the relative mass of the rifle was slightly greater for the women compared to the men (~ 5.6 *vs.* 5.0%, respectively; *Studies I–IV*), the responses to rifle carriage were similar for both sexes, with the only difference being a larger decrease in thorax (x) ROM during skiing WR for the women compared to the men.

Under control (i.e., "normal") conditions, only ~ 10% of the athletes' endurance-based training was performed while carrying the rifle and one additional training session·week^{-1} (~ 2 h·week^{-1}) WR for ~ 16 weeks did not affect physiological variables or improve roller-skiing performance compared to normal training (*Study II*).

This thesis improves the knowledge of the unique demands of biathlon skiing, which may be important for developing sport-specific training. The small margins between athletes at high performance levels increase the importance of even small details and this thesis demonstrate that the responses to rifle carriage seems to differ between individuals. To improve biathlon skiing performance training WR may be individualized to each athlete, with specific focus on training intensities and technique development when skiing with rifle.

9 Future directions

This body of work has increased the knowledge of the unique demands of biathlon skiing, but has also raised new questions to be answered in the future.

This thesis showed that rifle carriage increases breathing frequency and alters the movement of the upper body and COM. This may increase the demand on the respiratory muscles and stabilizing muscles in the trunk, which may lead to a faster onset of fatigue compared to skiing NR. In turn, this may increase body sway, which can impair standing shooting performance. However, this needs to be investigated in future studies.

Study II is to the author's knowledge the first to measure the amount of training performed WR in biathlon, and the effects of additional training WR. However, the study was carried out during the summer and the volume of rifle carriage training may differ at other periods throughout the year. Future studies should aim to determine the training performed WR during a whole year of training and to investigate whether there are any differences in rifle carriage training between biathletes at different levels or ages.

Most importantly, this thesis shows how rifle carriage affects physiological and biomechanical variables during biathlon skiing. From these results, recommendations for sport-specific biathlon training have been made. However, these recommendations need to be tested and evaluated, which should be an overarching aim for future research.

10 Training applications

The following points can be taken into consideration when planning, performing and analyzing biathlon training to help manage the physiological and biomechanical demands of rifle carriage in biathlon skiing.

- **Consider additional methods to measure training intensity when skiing WR**. Since HR does not reflect the increased respiratory and metabolic demands caused by rifle carriage, actual training intensity may be higher than planned when skiing WR if HR is used to prescribe and monitor training. As such, it may be useful to combine different measurements of intensity (e.g., BLa, RPE and/or accelerometers) during training and/or to make sure that the recovery is sufficient after training sessions WR to optimize the training response.

- **Train WR at the right intensities.** Since $speed_{4mmol}$ and MR_{an} decreased when skiing WR, and these two factors together explained ~ 80% of the variation in TT performance WR, it may be beneficial to perform a high amount of the high-intensity training (≥ LT) WR.

- **Perform skiing technique training at high intensities WR.** Since rifle carriage alters the ROM in the upper body and speed increases whole body and equipment ROM, biathletes are recommended to perform their skiing technique training under competition-like conditions.

- **Actively work to reach a high body position at PP when skiing WR.** Rifle carriage lowered the body position ($vert_{dist}$)

compared to skiing NR and decreased the distance covered and time spent in gear 3. By aiming to increase the $vert_{dist}$ of the biathletes during skiing WR, the force production on the poles may increase through a more effective use of the body mass to create force. With a more effective use of the upper body, the distance covered and time spent in gear 3 may also increase, which could lead to improved biathlon skiing performance.

- **Individualizing and planning sport-specific training.** There are individual variations in physiological and biomechanical responses to rifle carriage, which should be taken into consideration when planning, performing and evaluating biathlon training. Considering variables such as duration, intensity and focus of the different training sessions WR, as well as strength training and eventual periodization in rifle carriage training, is advisable.

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