

Review

The influence of physiobiomechanical parameters, technical aspects of shooting, and psychophysiological factors on biathlon performance: A review

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Abstract

The biathlon, an Olympic sporting discipline that combines cross-country skiing with rifle marksmanship, entails considerable physiological demands, as well as fine motor control while shooting after intense exercise and under mental pressure. Although much of our knowledge about cross-country skiing is probably also applicable to the biathlon, carrying the rifle and shooting under stress make this discipline somewhat unique. The present review summarizes and examines the scientific literature related to biathlon performance, with a focus on physiological and biomechanical factors and shooting technique, as well as psychophysiological aspects of shooting performance. We conclude with suggestions for future research designed to extend our knowledge about the biathlon, which is presently quite limited.

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1. Introduction

The biathlon, an Olympic sport that combines cross-country skiing with skating technique and small-bore rifle marksmanship,¹ entails considerable physiological demands similar to those associated with competitive cross-country skiing,² while also emphasizing accurate fine motor control during shooting after intense exercise and under mental pressure.³ In addition to increasing the physiological demands, carrying a rifle on the back may influence the biomechanics of skiing.⁴

However, the biathlon has been studied relatively little, as reflected in the fact that an up-to-date search in PubMed with “biathlon” as a keyword currently results in 79 hits, whereas a similar search with “cross-country skiing” yields almost 10 times as many hits. Although much of our present knowledge concerning cross-country skiing and rifle shooting may be applicable to the biathlon, carrying a rifle while skiing and

shooting under stress while recovering make this sport somewhat unique with respect to the influence of physiobiomechanical and psychophysiological factors, as well as shooting technique.

2. History of the biathlon

The biathlon has been a regular event in Olympic Games since 1960. In the beginning, biathletes used high-power cartridges and the distance from the shooting ramp to the targets varied between 100 m and 250 m. Later, in 1978, shooting was standardized (0.22-inch ammunition and small-bore rifles) and the target distance reduced to 50 m. Metal targets replaced the original paper ones in the 1980s, at which time females were also allowed to participate, with the female’s biathlon becoming part of the Winter Olympic Games in 1992. Today’s biathlons include several individual distances and relays, and, indeed, the biathlon was one of the first sporting disciplines with mixed relay teams consisting of both male and female.⁵

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3. The basics of the modern biathlon

A schematic overview of an arena in which biathlon competitions take place is shown in Fig. 1. The overall finishing time is based on skiing time (speed) as well as shooting accuracy and speed. Today, there are 6 different types of biathlon competitions, including the sprint (7.5 km for female and 10 km for male, shooting prone (P) and standing (S)); pursuit (10 km for female and 12.5 km for male, P + P + S + S); mass start (12.5 km for female and 15 km for male, P + P + S + S); individual (15 km for female and 20 km for male, P + S + P + S); relay (4 × 6 km for female and 4 × 7.5 km for male, 4 × P + S); and mixed relay (2 × 6 km for female + 2 × 7.5 km for male, 4 × P + S).

During competition, each time the biathlete enters the range, she or he fires 5 shots at 5 targets 50 m away, either while prone or standing (Fig. 2). These targets are 11.5 cm in diameter, with a hit diameter of 4.5 cm when prone and 11.5 cm when standing. Individual events (the men's 20 km and women's 15 km) involve a 1-min penalty for each shot missed. For all other events, for each shot missed a 150-m penalty loop (approximately 25 s) must be skied before returning to the race course. In the case of relays, the biathlete has 3 additional shots per shooting station.^{5,6}

4. Skiing performance

4.1. The demands of biathlon skiing

Skiing time during a biathlon varies from approximately 15 min in the sprint to approximately 45 min in individual competitions. During this skiing, the heart rate (HR) is approximately 90% of maximal HR (HR_{max}), decreasing slightly as the shooting station is approached and decreasing to approximately 70% and 60% of HR_{max} while shooting in the prone and standing positions, respectively.² Since the introduction of the skating technique in the 1980s, biathlon skiing speed, like

cross-country skiing speed,⁷ has increased to become approximately 7% faster at present than during the 2001/2002 season⁶ (Fig. 3). Today, the average skiing speeds of the 10 best biathletes in World Cup biathlon sprint competitions are 7.2 m/s for male and 6.3 m/s for female athletes.⁸

It should be noted that these averages are confounded by various factors, such as the location of the event and weather during the competition. Indeed, racing time is prolonged by 2% for every 1000-m increase in altitude, 5% per 1% increase in incline, 1%–2% per 1 m/s elevation in wind speed, and 2%–4% when changing from packed snow to softer snow.⁹ The increments in average speed may be due in part to alterations in training regimens (e.g., training for upper body strength and endurance, speed, and technique), as in the case of cross-country skiers,^{10–13} but also to improvements in skis and waxes as well as preparation of the course/snow and skis. These increases in skiing speed may also change the physiological and biomechanical requirements for effective biathlon skiing, a topic that requires further investigation.

Luchsinger et al.⁸ showed recently that approximately 60% of overall performance in biathlon sprint competitions is determined by skiing speed. However, in individual competitions, where each shot missed results in a 1-min penalty, shooting performance is probably more important. However, the impact of skiing speed, shooting time, shooting accuracy, and, potentially, tactics, as well as pacing on overall performance in pursuit and mass start competitions, is currently unknown.

4.2. Different skiing subtechniques

In the modern biathlon, skating is the only skiing technique used. As in cross-country skiing, this skating encompasses several gears (subtechniques), with which the biathlete adapts to the skiing speed and terrain.¹⁴ In general, lower gears are used on uphill sections and at slower

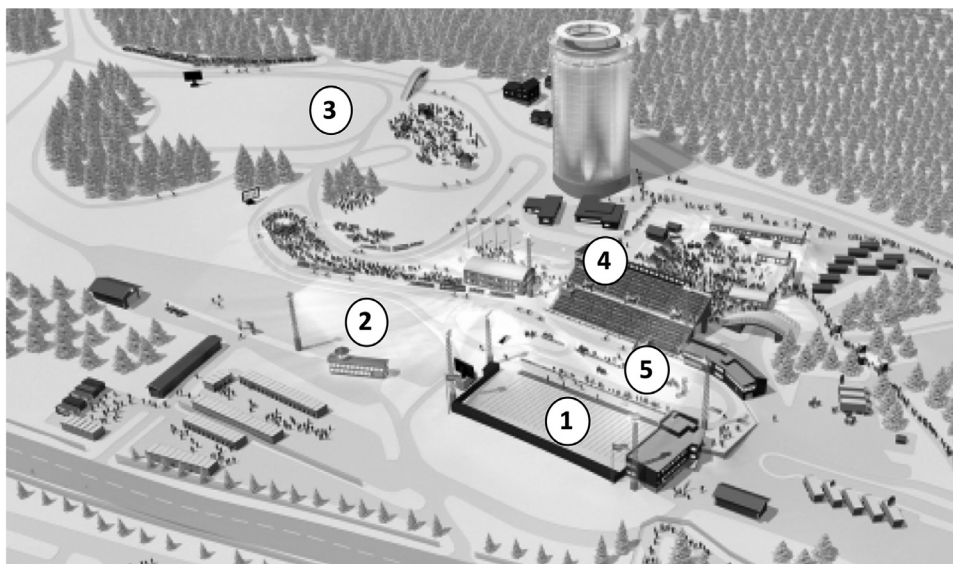


Fig. 1. Overview of the Swedish National Biathlon Arena in Östersund, Sweden, including the shooting range (1), penalty loop (2), skiing tracks (3), spectator stand (4), and start and finish areas (5). Illustration by Ulf Nygren.

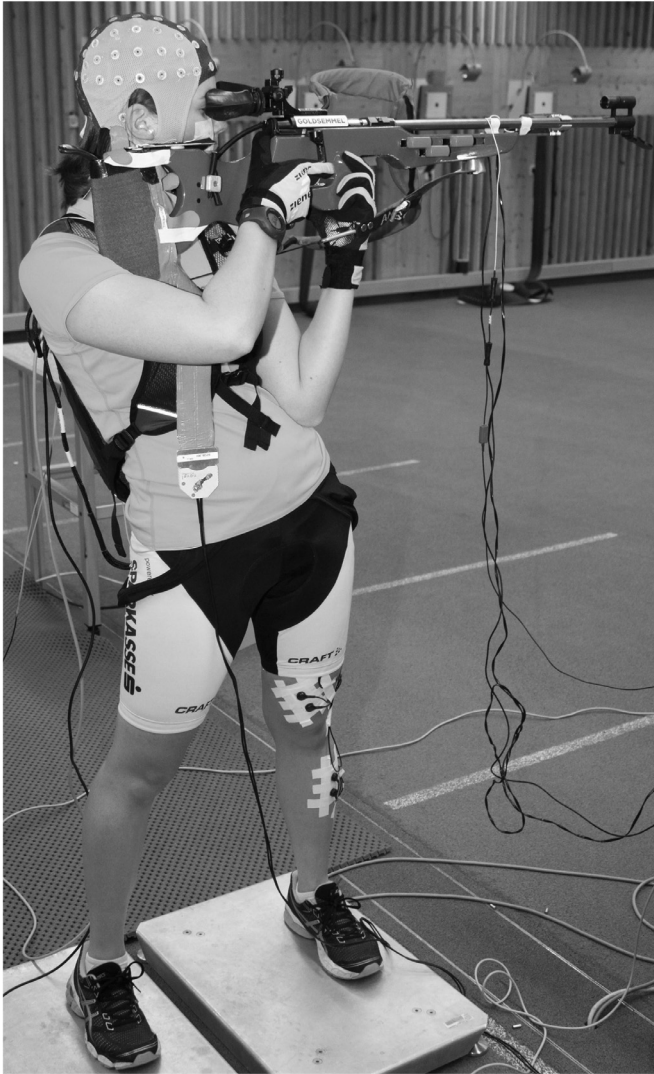


Fig. 2. Measurement of relevant parameters during biathlon shooting in the standing position.

velocities and higher gears are used on flatter and downhill sections and at higher speeds.

In the case of cross-country skiing, Gears 2 and 3 (sometimes also referred to as V1 and V2) are used most frequently.¹⁵ Gear 1 is used only on very steep uphill terrain during training. Gear 2, used solely on uphill terrain, involves nonsymmetrical poling in combination with work by the legs, whereas Gear 3 (symmetrical poling with leg work) is usually applied on moderate uphill or even on flat terrain. The proposal that the time spent on uphill sections is the most important determinant of the finishing time of a cross-country skier¹⁶ emphasizes the key importance of Gears 2 and 3.

4.3. Determinants of biathlon skiing performance

A biathlon competition consists of 3 or 5 high-intensity bouts of skiing, each lasting 5–8 min depending on the type of competition,⁶ and separated by a short break (approximately 25–30 s) while preparing and performing the shooting.

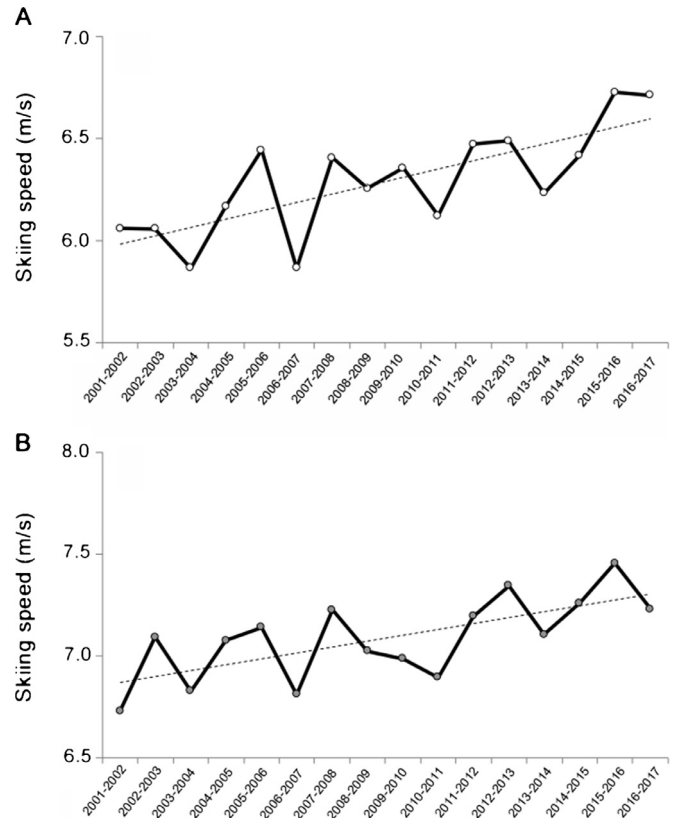


Fig. 3. Increases in the average biathlon skiing speed for females (A) and males (B) from the 2001–2002 to the 2016–2017 season. Each data point represents the average skiing speed of the first 5 finishers in 4 annual biathlon World Cup sprint events (Östersund, Sweden; Hochfilzen, Austria; Oberhof, Germany; and Oslo, Norway).

Therefore, the biathlon is classified as an endurance sport, where the impact of aerobic energy metabolism on overall performance is significant.¹⁷ More generally, endurance performance depends on both aerobic and anaerobic factors, together with exercise economy and/or gross mechanical efficiency.^{17,18} It has been proposed that the 56-km classical cross-country skiing race results in both peripheral and central fatigue,¹⁹ whereas for a shorter race (e.g., simulated sprint competition) the fatigue may be only peripheral.²⁰ Thus, in the case of the biathlon, both peripheral and central fatigue may be experienced and affect both skiing performance and shooting accuracy.

In one of the few studies performed on biathlon skiing to date, Rundell and Bacharach²¹ showed that peak oxygen uptake (VO_{2peak}) correlated with skiing time during the 20-km competition, but only for males. In another investigation, Rundell²² found that maximal oxygen consumption (VO_{2max}) and the lactate threshold exhibit moderate correlations with roller skiing performance by female biathletes. Similar results have been reported for both female²³ and male²⁴ cross-country skiers, for whom gross mechanical efficiency is also related to performance.²⁵

Because the best biathletes can also compete in cross-country skiing at an elite international level, the requirements for

Table 1

The $\text{VO}_{2\text{max}}$ of Norwegian female and male biathletes and cross-country skiers who won Olympic and/or World Championship medals between 1990 and 2013 (mean \pm SD).

	<i>n</i>	$\text{VO}_{2\text{max}}$ (mL/kg/min)	$\text{VO}_{2\text{max}}$ (L/min)
Female			
Biathlon skiers	7	66 \pm 5	4.0 \pm 0.2
Cross-country distance skiers	10	73 \pm 5	4.3 \pm 0.3
Cross-country sprint skiers	5	69 \pm 4	4.3 \pm 0.4
Male			
Biathlon skiers	8	81 \pm 3	6.2 \pm 0.6
Cross-country distance skiers	17	84 \pm 5	6.4 \pm 0.6
Cross-country sprint skiers	7	78 \pm 3	6.3 \pm 0.6

Table modified from Tønnesen et al.,¹⁰⁸ with permission.

Abbreviation: $\text{VO}_{2\text{max}}$ = maximal oxygen consumptions.

aerobic capacity made by these 2 disciplines are likely to be similar. This comparison is summarized in Table 1. Taken together, these findings indicate that a high $\text{VO}_{2\text{max}}$, lactate threshold, and gross efficiency are essential for successful biathlon skiing performance. However, in the biathlon, as in cross-country skiing, uphill sections require power output higher than the $\text{VO}_{2\text{max}}$,^{26–29} which, together with the increasing average speeds, indicates that the anaerobic component is also a crucial determinant of performance.

In biathlon, carrying a rifle on the back while skiing increases O_2 consumption, HR, ventilatory responses, and blood lactate concentration, as well as accelerating the cycle rate and requiring more pronounced leg work.^{4,30} This finding is especially true for females, who typically weigh less than male, but carry a rifle of the same weight. However, data regarding the effects of carrying a rifle on biathlon skiing performance remain highly limited. Thus, it is of considerable interest to clarify these effects on, for example, skiing position (range of motion of the different joints), as well as the choice and use of different gears (subtechniques), including consideration of potential sex differences.

5. Biathlon shooting technique

Shooting performance is similar in both female and male biathletes. In normal weather conditions, the shooting accuracy (hit rate) during individual events at Olympic Games and World Championships is $>95\%$ among all medalists. In contrast with other shooting disciplines, research on biathlon shooting is, however, extremely limited (summarized in Table 2). Performance in this context is determined primarily by the prior intense skiing, shooting time, changes in weather conditions, and specific features (e.g., surface, stance on skis, etc.) of the shooting range.^{31,32} The few previous investigations of relevance have focused on individual characteristics (e.g., body and rifle sway) and comprehensive, and systematic biomechanical studies in both the prone and standing shooting positions under highly stressful conditions are lacking.^{33,34} Biathlon training often involves the use of laser tracking of the rifle barrel, force platforms to determine and modify body sway, and/or video

analysis of body position and shooting mechanics; however, little information on these aspects has yet to be published.

5.1. Postural balance

Studies on rifle, pistol, and biathlon shooting have focused on postural balance in the standing situation and have shown stance stability to be a key factor for successful performance. Elite male and female shooters show less body sway than non-elite shooters,^{35–40} and this clearly distinguishes high-level from low-level shooters.^{32,33,41–45} Accordingly, Era et al.³⁷ have recommended specific balance training, primarily for young and inexperienced shooters. Moreover, biomechanical biofeedback can also improve the postural stability of top-level shooters.⁴⁶

At the same time, specific shooting stances may also improve stability. In this context, it has been shown that standing at an angle of 15° to the line of fire results in the best overall performance by air pistol shooters. However, positioning when shooting a rifle differs, and, in general, few kinematic studies on shooting positions have been reported.⁴⁷ In contrast with competitive rifle shooters, the biathlete has very limited time in which to find the optimal position, making the relationship between shooting position and performance particularly important in this context.

Previous investigations on biathlon^{32,33,48} and rifle shooting^{39,49} have revealed a pronounced relationship between body sway and motion of the rifle. In other words, poor stance stability is associated with an unstable hold on the rifle, which results in poor and variable shooting.^{32,36,39}

With respect to stance, the anteroposterior (AP) direction (across the line of fire) is the best predictor of shooting scores³³ and clearly distinguishes experienced shooters from novices.^{32,37} Moreover, body sway in the AP direction is significantly higher than in the mediolateral (ML) direction (along the line of fire).^{32,40,50} In the case of biathlon shooting, muscle fatigue increases ankle joint motion, resulting in more pronounced destabilization in the AP than in the ML direction.³³

In general, posture is destabilized by exercise^{51–53} and metabolic activation, with increases in both heart and breathing rate under aerobic and anaerobic load.^{54,55} Furthermore, comprehensive training designed to improve coordination, strength, range of motion, and reaction to proprioceptive demands strengthens balance.⁵⁶ Such training and the resultant development of hip/ankle strategies⁵¹ might explain the differences in the stance stability of high-level and young biathletes after an intense physical load.³³ In any case, the well-recognized negative effect of physical exercise (e.g., on roller skis, a bicycle, or skis) on postural balance^{31,40,57–59} is of fundamental importance in connection with biathlon shooting. In this context, Sattlecker et al.⁵⁸ have demonstrated that lower body work exerts a greater negative impact on stance stability than upper body exercise.

Prone shooting is also influenced by the more rapid breathing and HR caused by exercise,⁶⁰ but to a lesser extent than shooting in the standing position.⁶¹ As mentioned, the HR

Table 2
A summary of peer-reviewed studies on biathlon shooting technical factors and shooting performance.

Reference	Aim	Subjects	Major findings
Baca and Kornfeind (2012) ⁶³	To analyze the stability of aiming by elite biathletes	World Cup ($n = 4$) and European Cup ($n = 5$) biathletes	The video-based system revealed that the top-level athletes exhibited more stable horizontal and vertical motion of the muzzle
Grebot and Burtheret (2007) ⁷⁰	To measure the forces exerted on the butt plate by the shoulder of the biathlete during prone and standing shooting	2 males and 2 females members of a national team (age: 26.5 years)	Athletes showed lower force on the butt plate in the prone position owing to fatigue. In general, this force during prone shooting was higher than when standing. The authors also found a difference between these 2 positions with respect to positioning of the butt plate on the shoulder
Groslambert et al. (1998) ¹⁰⁹	To investigate the cardioventilatory responses of elite biathlon athletes when shooting while standing	3 males, 1 female member of a national team (Olympic participants)	Reduced ventilatory exchange was suggested to enhance the ability to hold the rifle effectively
Groslambert et al. (1999) ⁴¹	To validate 3 simple tests of biathlon shooting abilities—visual reaction time in both the standing and prone positions as well as a tremometer test in the standing position	24 subjects (19 males, 5 females) at 2 different levels: national team members ($n = 12$; age: 20 years) and nonexpert members of a regional team ($n = 12$; age: 19 years)	Visual reaction time and the results of the tremometer test were correlated with shooting performance
Groslambert et al. (2003) ⁶⁷	To examine the effects of autogenic and imagery training on stability of hold, heart rate, and standing shooting performance after heavy physical exercise	16 members (12 males, 4 females) of a national team (age: 21.5 years)	A training program including autogenic and imagery content improved standing shooting performance substantially by increasing postural control and holding ability
Hoffman et al. (1992) ³¹	To assess the shooting performance of elite biathletes immediately after exercise of varying intensity	13 members (6 males, 7 females) of a national team	Exercise intensity had minimal effect on shooting accuracy in the prone position, but did affect standing shooting by altering the stability of hold
Ihalainen et al. (2018) ⁴⁸	To identify determinants of biathlon standing shooting performance at rest and after intense exercise	17 subjects (11 males, 6 females) at 2 different levels: a national senior ($n = 8$; age: 25.5 years) and national junior team ($n = 9$; age: 17.9 years)	Clean triggering (i.e., motion of the aiming point 0–0.2 s before firing) and vertical stability exerted most influence on shooting performance both at rest and after exercise. Postural balance, mainly in the shooting direction, was related to the cleanliness of triggering and vertical holding ability
Laaksonen et al. (2011) ⁶⁸	To test the hypothesis that combined relaxation and specifically designed shooting training enhance shooting by biathletes	20 subjects (13 males, 7 females) at the national and international (up to World Cup) levels; age: 20 years for the experimental group and 19 years for the control group	Combined relaxation and specific shooting training (holding and routine shooting maneuvers without ammunition) enhanced shooting performance
Larue et al. (1989) ¹¹⁰	To compare the body–gun stability of biathletes and rifle shooters in the standing position	8 subjects: 2 experts and 2 novice rifle shooters, 2 experts and 2 novice biathlon shooters	Expert biathlete and rifle shooters use different strategies regarding rifle oscillation and center-of-pressure-displacement, adapting to their respective disciplines
Niinimaa and McAvoy (1983) ⁴⁰	To analyze stance stability while standing at rest with and without aiming an air rifle. Body sway was measured at rest and after a bout of simulated cross-country ski racing	16 males subjects: a control group with no previous shooting experience, groups of rookie and established biathletes, and experienced rifle shooters	Body sway was greater during aiming than while simply standing at rest, and also greater during aiming after exercise than at rest. Body sway was less in experienced shooters than rookies. Motion in the anteroposterior direction was approximately twice the lateral movement
Sattler et al. (2014) ³²	To compare the biomechanics of young and elite biathletes and to examine the relationship between rifle and body sway and shooting performance	36 subjects (27 males, 9 females) at 3 different levels: World Cup ($n = 8$; age: 27.4 years), European Cup ($n = 13$, age: 20.2 years), young athletes ($n = 15$, age: 17.4 years)	Young athletes demonstrated more pronounced rifle and body sway than World and European Cup athletes. Rifle and body sway were correlated with the shooting score, mainly across the shooting direction
Sattler et al. (2017) ³³	To identify factors discriminating high- from low-scoring biathletes both at rest and under loading	22 subjects (14 males, 8 females) at 3 different levels: World Cup ($n = 7$; age: 24.3 years), European Cup ($n = 7$, age: 21.1 years), young athletes ($n = 8$, age: 16.6 years)	With prone shooting, shoulder force in the resting condition and vertical rifle motion after intense roller skiing were the main discriminators between high- and low-scoring athletes. In the case of standing shooting, several parameters related to body and rifle sway were discriminators at rest
Simoneau et al. (1997) ⁵⁹	To analyze metabolic activation and its effects on the stance stability and shooting performance of biathletes	Recreational athletes and highly skilled biathletes	Metabolic activation, induced by skiing, decreases postural control during biathlon standing shooting. The authors also found that skilled athletes were less affected by fatigue, suggesting that skill can attenuate this influence of fatigue on balance control

declines as the biathlete stops skiing and commences shooting. During shooting, it is usually 60%–70% of HR_{max} if standing and even lower during prone shooting² owing to reactivation of cardiac parasympathetic nerves.⁶² Tharion et al.⁶⁰ have reported that in the prone position the HR slows even faster because of the more pronounced improvements in blood and oxygen supply to the brain.

5.2. Rifle stability

Rifle stability, an important determinant of high-level performance in both biathlon shooting and several other shooting disciplines, is closely related to shooting scores while standing^{39,41,43,63} and distinguishes high- from low-scoring male and female athletes.^{32,33,43,45,64,65} Moreover, extensive vertical sway exerts a negative effect on shooting accuracy at rest.^{45,66} Ihalainen et al.⁴⁸ discovered cleanliness of triggering (i.e., the motion of aiming point 0–0.2 s before the shot) and, once again, vertical stability of hold to be the most important determinants of shooting performance at rest and under load conditions.⁴⁸ In contrast, changes in air rifle shooting performance from training to competition were most strongly related to alterations in the horizontal hold on the rifle.⁴⁹

Differences in the athlete's level of skill and the particular discipline involved (air rifle vs. running target shooting) may explain at least some of the discrepancies between these reports. In running target shooting, the athlete must follow the target in the horizontal direction, and therefore the ability to stabilize the rifle in the vertical direction is essential. In connection with air rifle shooting, as well as biathlon shooting,⁵⁷ horizontal movement is the major factor that discriminates high- from low-level athletes. This may reflect the relationship between rifle and body sway; Sattlecker et al.³² found a strong relationship between displacement of the center of mass in the AP direction and horizontal rifle sway. In general, previous physical exercise exerts a negative influence on how the rifle is held during biathlon shooting in the standing position,^{31,33} increasing the movement of the rifle by as much as 50%, with the rising center of pressure after a physical load indicating the interrelationship between these 2 variables.³³

In the case of prone shooting, Hoffman et al.³¹ observed only minimal effects of exercise intensity on rifle stability, whereas Sattlecker et al.³³ found the vertical sway of the barrel to be the main predictor of prone performance after physical exercise. The recent alterations in breathing and aiming strategies required by more rapid shooting may explain at least some of the differences between these 2 studies.

In general, specific holding and relaxation training can improve rifle stability and thereby improve shooting accuracy.^{67,68} Furthermore, biomechanical biofeedback has been reported to improve the barrel stability of high-level shooters.⁴⁶ To extend our understanding of the significance of rifle positioning, future investigations in this area should combine kinematic with kinetic analyses.

5.3. Shoulder forces

The butt plate of the rifle should be fixed against the shoulder and held isometrically by the elbow flexors.⁶¹ A stock of optimal length⁶⁹ and substantial contact between the rifle and shoulder⁷⁰ improve the hold on the rifle. Moreover, holding the rifle butt tightly against the shoulder results in better horizontal rifle stability.³³ Previous physical exercise often results in lower rifle forces on the shoulder, attenuating the stability of the rifle, particularly when shooting in the prone position.^{33,70} Thus, fatigued elbow flexors may produce lower shoulder forces, thereby impairing rifle hold and accuracy.⁶¹ More detailed knowledge concerning shoulder forces should help trainers and athletes to find the optimal rifle length and ideal shape of the butt plate.

5.4. Triggering

The fine motor control involved in triggering during biathlon⁴¹ and other types of shooting has scarcely been examined, even though it has been argued that triggering behavior is a major predictor of biathlon shooting performance.^{71,72} Moreover, trigger forces before shooting at rest while standing were higher in elite male and female athletes compared to young biathletes.⁷³ In general, physical exercise before shooting decreased trigger forces,⁵⁷ at least for low-scoring biathletes, but not for high-scoring male and female biathletes.⁵⁷ The appropriate timing of finger movement was impaired by fatigue, an effect that could be compensated for by new patterns of motor coordination.⁷⁴ Thus, in contrast with young athletes, elite biathletes might have developed motor strategies that allow precise neural control of the distal joints and consistent triggering behavior, even when fatigued. Furthermore, Sattlecker et al.³³ observed moderate correlations between triggering behavior and rifle stability during prone shooting. These findings highlight the importance of triggering in connection with biathlon shooting, but detailed and systematic investigations on this topic are sorely needed.

6. Psychophysiological aspects of biathlon shooting

Biathlon shooting involves a complex situation, affected not only by factors such as physical load before shooting, time pressure, other competitors, and the necessity for fine motor control, but also by psychological and, especially, psychophysiological factors. Although the assessment of psychophysiological aspects of competitive shooting has a long tradition,⁷⁵ biathlon shooting is underresearched in this respect. Scientists have only just recently begun to show interest in examining the cardiac^{76,77} and cortical activity,^{78,79} skin conductance,⁸⁰ gaze behavior,⁸¹ and breathing patterns⁸² in this context.

Hatfield et al.⁸³ characterized rifle shooting from the perspective of “ocular fixation, minimal muscular involvement, attention to autonomic control, focused concentration on target cues, and an inhibition of environmental distraction” (p. 543). Current findings reveal that focused attention,⁸⁴ visuomotor processing designed to anticipate the optimal moment at which

to pull the trigger, and psychomotor regulation of large and fine groups of muscles⁸⁵ are all required for successful shooting. Among other approaches, the aiming phase by groups with different levels of expertise⁸⁶ and/or in connection with the best and worst shots by one and the same biathlete⁸⁷ was compared.

6.1. Cardiac activity and shooting

Konttinen et al.⁷⁷ observed a decrease in HR before triggering by both elite and nonelite male shooters. Basing their reasoning on the intake-rejection hypothesis,⁸⁸ these authors proposed that this decrease reflects an outward-directed attentional focusing, although the extent of the decrease was not associated with shooting scores. Moreover, Helin et al.⁷⁶ demonstrated that elite male and female shooters pull the trigger during diastole (when the heart ventricles are relaxed and filling), with beginners firing during both diastole and systole, with better results during diastole.

Upon examining the cardiac cycle in greater detail, Konttinen et al.⁸⁹ found that nonelite male rifle shooters performed above average when they shot during the initial 0–50% or final 70%–99% of the R-R interval (the period between adjacent heartbeats). These authors argued that the “critical factor is not the heart relaxation, but the mechanical movement caused by the heart muscle contraction” (p. 400). This movement reaches its maximum between 400 and 600 ms through 1 cycle, which corresponds with approximately 51%–69% of the R-R interval. These observations are in contrast to those of Mets et al.,⁹⁰ who found no relationship between the timing of triggering within the cardiac cycle and shooting performance by elite junior male and female rifle shooters. Clearly, further study designed to clarify the optimal timing of shooting is required.

In the case of biathlon shooting, it is assumed that the timing of the shot within the cardiac cycle is probably more influential than with sport shooting because of the pronounced cardiovascular load of the preceding skiing, which perturbs visuomotor control and psychomotor regulation. Accordingly, biathletes may benefit from biofeedback that promotes triggering during the R-R interval of a cardiac cycle, as proposed by Mets et al.⁹⁰ Of additional importance is the decrease in shooting time (the time between entering and leaving the shooting mat) that has occurred during the last few decades. For example, the average shooting time for the 10 best male biathletes in the 20-km individual competition was 27.9 s at the World Championships in 2017⁹¹ vs. 33.5 s in 1997⁹². The question then arises as to whether more rapid triggering alters the optimal placement of the shot within the R-R interval and in relation to breathing.

6.2. Cortical activity and shooting

In numerous articles, Konttinen et al.^{42,64,79,82,93,94} have evaluated the slow brain waves of shooters 7.5 s before and 1.5 s after pulling the trigger. Before the shot, slow brain potentials decrease monotonically until the trigger is pulled,⁸² and this phenomenon is enhanced by aiming and attenuated by

holding the rifle for stability. In line with these findings, these investigators reported that, in connection with successful shots by both experienced elite and subelite male shooters,⁹⁴ frontal positivity is an indicator of motor activity, whereas right-sided negativity reflects visuospatial processing. Consequently, they concluded that slow brain potentials provide information concerning the optimal balance between aiming and motor processes, information that may be of value in connection with diagnostic approaches.

Spectral analyses, most of which have focused on the alpha band at 8–12 Hz, have demonstrated that experienced right-handed male and female shooters with an ipsilateral hand-eye dominance exhibited a larger band (indicative of less activation) in the left temporal area than the right hemisphere during the preshot phase.⁷⁸ This finding, since confirmed several times,^{81,95–97} has been interpreted as less pronounced verbal and analytical processes in experienced shooters than in novices.⁹⁶ With respect to the visual domain, Loze et al.⁹⁷ detected a larger occipital alpha band before best shots, suggestive of more pronounced suppression of visual attention than before worst shots. These authors argued that excessive visual attention might interfere with the motor program involved in automatic aiming, which is controlled by mechanisms of intention. Thus, in the context of the biathlon, visualization of one’s own and/or an opponent’s performance may have a negative impact on shooting.

Functional changes in the electroencephalogram (EEG) can be quantified as the percentage change in signal strength before the shot. Increases and decreases are referred to as event-related synchronization (ERS) and event-related desynchronization (ERD), respectively.⁹⁸ Applying this approach to the entire scalp, Del Percio et al.⁹⁹ observed less ERD in the low (8–10 Hz) and high (10–12 Hz) regions of the alpha band of elite male and female shooters during the preparatory phase in comparison with nonathletes. In association with the best shots of elite athletes, the ERS at high α frequencies was enhanced, specifically at the right and parietal sites. The neural efficiency hypothesis¹⁰⁰ postulates lower global activation in athletes than in nonathletes, as well as a specific ERS pattern localized to certain regions of the brain during successful shots.

Another approach, EEG coherence analysis, addresses functional communication between different areas of the brain on the basis of correlations in the amplitudes of signals of a given frequency at 2 locations.¹⁰¹ High coherence indicates communication, whereas low coherence reflects regional autonomy or independence.¹⁰² Upon analyzing the low alpha, high alpha, and low beta band frequencies, Deeny et al.¹⁰¹ found that expert male and female shooters showed less corticocortical communication than skilled shooters, which was interpreted as reduced cognitive involvement in aiming. A subsequent investigation provided evidence that cortical networks become more refined as expertise is gained.¹⁰³

Few such studies have focused on the theta band at 4–8 Hz,^{84,96} which is associated with concentration¹⁰⁴ and internalized attention.¹⁰⁵ Doppelmayr et al.⁸⁴ demonstrated a continuous increase in the amplitude of this theta band in the frontal midline region (Fm θ) during the 3 s immediately

before shooting by male experts, but not novices whose shooting was significantly less accurate. These researchers concluded that experts and novices use different aiming strategies, with enhanced attentional focus on triggering by the experts only.

6.3. Gaze behavior and shooting

Upon comparing the gaze behavior and cortical activity of expert and nonexpert shooters, Janelle et al.⁸¹ detected more prolonged fixation on the target immediately before the shot by the experts. This gaze strategy, termed quiet eye,¹⁰⁶ is considered to be an objective measure of visuomotor control, influencing attentional control, response programming, and external focus.¹⁰⁷

6.4. Studies specifically on biathlon shooting

Our search of PubMed on March 3, 2018, revealed only 3 psychophysiological investigations of biathlon shooting, specifically on the impact of preceding physical load on rifle shooting. Vickers and Williams³ analyzed the physiological arousal, cognitive anxiety, and gaze behavior of 10 male and female members of national junior and senior biathlete teams while shooting at rest and after exercise at 55%, 70%, 85%, or 100% of their VO_{2max} and under low or high psychological pressure. After exercise at 100% VO_{2max} , 58% of the adjusted difference between low- and high-pressure scores could be accounted for by the duration of the quiet eye and ratings of perceived exertion. After such a maximal load, biathletes who performed well even under high pressure (nonchokers) maintained their quiet eye longer under high than low pressure. Thus, by focusing visual attention on the target, biathletes might be able to avoid choking, even after a high physical load and when under stress.

Luchsinger et al.⁸⁶ reported that male and female biathletes exhibited better shooting performance and had higher $Fm\theta$ (frontal-midline theta activity) than cross-country skiers, both when shooting without preceding physical load and after 6-min bouts of roller ski skating at 85% of HR_{max} . In addition, submaximal exercise exerted no effect on the shooting accuracy or $Fm\theta$ of either biathletes or cross-country skiers, which, it was argued, may have been due to their considerable fitness. In another EEG analysis of $Fm\theta$ and α activity in young male and female biathletes, Gallicchio et al.⁸⁷ found that shooting accuracy with no preceding load and after 3 min of cycling at 90% of HR_{max} was the same. In contrast with the observations of Luchsinger et al.,⁸⁶ $Fm\theta$ was lower with preceding loading than without. This discrepancy may be explained by the differences in age and level of fitness of the participants and the different physical loads applied, which might have influenced focused attention.

Moreover, the magnitude of the α band over the temporal and occipital, but not the central, regions can be elevated, indicating a compensatory strategy for maintaining shooting performance even after intense cardiovascular load. Better performance after loading was associated with higher $Fm\theta$ and

less intense left central and higher left temporal α bands.⁸⁷ These findings support the conclusion that neural efficiency, as indicated by prolonged inhibition of regions of the brain not involved in movement and activation of those involved, is beneficial to biathlon shooting.

Altogether, these findings indicate that a successful biathlete must have good body perception and self-regulation to anticipate the optimal time point for shooting. This time point seems to be related to the cardiac cycle and a continuous increase in attention (as indicated by the $Fm\theta$) before triggering. Accordingly, it has been proposed that appropriate biofeedback could improve the shooting performance of biathletes.

7. Conclusion

The start-and-stop nature of the biathlon, with periods of high-intensity skiing separated by short intervals of recovery during which shooting is performed, is unique, but research on the physiological responses during biathlon competitions is currently quite limited. Obviously, this discipline requires effective delivery of oxygen and excellent skiing skills. The available literature on biathlon and related sporting disciplines indicates that both a high lactate threshold and gross mechanical efficiency, in combination with pronounced aerobic capacity, are essential to superior skiing performance. At the same time, this overall performance also depends on shooting speed and accuracy and, indeed, several other factors, such as body sway, rifle stability, and triggering behavior. The preceding physical load undoubtedly alters psychophysiological processes associated with the complex task of aiming, which involves considerable arousal/activation. This is affected strongly by postural and rifle stability, and places great demands on focused attention.

8. Future perspectives

An important factor that has been taken into consideration by only a few studies is how carrying a rifle influences the biomechanics and/or choice of different subtechniques during biathlon skiing. This factor is of particular interest for female biathletes because they weigh less but carry a rifle of the same mass that males carry. Future studies should, therefore, focus on possible gender differences. In addition, detailed and systematic biomechanical analysis of shooting in both the prone and standing positions under highly stressful conditions, as well as investigation of the relationship between shooting position and performance, would provide a more solid scientific basis for future development. In addition, the optimal timing of a shot within the cardiac cycle needs to be clarified further. Finally, we recommend more extensive examination of cortical EEG signals related to movement, both in the form of coherence analysis and the ERD/ERS ratio. In particular, a better understanding of the relationship between intense preceding cardiovascular load, postural stability, and alpha as well as theta activity may help to improve neural efficiency and specificity in connection with the complex task of aiming.

Authors' contributions

MSL led the project, conceived of the study, performed the literature search, and contributed to writing and editing the paper; TF, HCH, and GS performed the literature search and contributed to writing and editing the paper. All of the authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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