

Review

Pacing and predictors of performance during cross-country skiing races: A systematic review

Thomas Stöggl^{a,*}, Barbara Pellegrini^{b,c}, Hans-Christer Holmberg^{d,e,f,g}

^a Department of Sport and Exercise Science, University of Salzburg, Hallein/Rif 5400, Austria

^b CeRiSM Research Centre “Sport, Mountain, and Health,” Rovereto 36068, Italy

^c Department of Neuroscience, Biomedicine and Movement, University of Verona, Verona 37100, Italy

^d Swedish Winter Sports Research Centre, Mid Sweden University, Östersund 83128, Sweden

^e School of Sport Sciences, UiT Arctic University of Norway, Tromsø 9037, Norway

^f School of Kinesiology, University of British Columbia, Vancouver, BC V6T 1Z1, Canada

^g Department of Physiology and Pharmacology, Karolinska Institutet, Stockholm 17177, Sweden

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Abstract

Background: Cross-country skiing (XCS) racing, a popular international winter sport, is complex and challenging from physical, technical, and tactical perspectives. Despite the vast amount of research focusing on this sport, no review has yet addressed the pacing strategies of elite XCS racers or the factors that influence their performance. The aim was to review the scientific literature in an attempt to determine the effects of pacing strategy on the performance of elite XCS racers.

Methods: Four electronic databases were searched using relevant subject headings and keywords. Only original research articles published in peer-reviewed journals and the English language and addressing performance, biomechanics, physiology, and anthropometry of XCS racers were reviewed.

Results: All 27 included articles applied correlative designs to study the effectiveness of different pacing strategies. None of the articles involved the use of an experimental design. Furthermore, potential changes in external conditions (e.g., weather, ski properties) were not taken into consideration. A comparable number of studies focused on the skating or classical technique. In most cases, positive pacing was observed, with certain indications that higher-level athletes and those with more endurance and strength utilized a more even pacing strategy. The ability to achieve and maintain a long cycle length on all types of terrain was an important determinant of performance in all of the included studies, which was not the case for cycle rate. In general, uphill performance was closely related to overall race performance, with uphill performance being most closely correlated to the success of female skiers and performance on flat terrain being more important for male skiers. Moreover, pacing was coupled to the selection and distribution of technique during a race, with faster skiers employing more double poling and kick double poling, less diagonal stride, and more V2 (double dance) than V1 (single dance) skating across a race.

Conclusion: We propose that skiers at all levels can improve their performance with more specific training in techniques (i.e., maintaining long cycles without compromising cycle rate and selecting appropriate techniques) in combination with training for endurance and more strength. Furthermore, we would advise less experienced skiers and/or those with lower levels of performance to apply a more even pacing strategy rather than a positive one (i.e., starting the race too fast).

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Keywords: Classic style; Competition; Cycle characteristics; Positive pacing; Skating

1. Introduction

Cross-country skiing (XCS) is one of the most demanding Olympic endurance sports, in large part because of the

pronounced physiological and technical challenges involved in coordinating upper- and lower-body efforts of varying intensity, varying duration, and on and hilly terrain, often at a moderate altitude and in a cold environment. The Olympic Games held recently in Pyeongchang, Republic of Korea, involved 6 different kinds of XCS races (Table 1).

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* Corresponding author.

E-mail address: thomas.stoeggel@sbg.ac.at (T. Stöggl).

Table 1
Race formats, applied skiing technique and distances for males and females at the 2018 Winter Olympics in Pyeongchang.

Format	Duration	Mode	Style
Middle distance			
Male	15 km	Individual time trial	Skating
Female	10 km		
Pursuit			
Male	30 km	Pursuit	1/2 classical + 1/2 skating
Female	15 km		
Long distance			
Male	50 km	Mass start	1/2 classical + 1/2 skating
Female	30 km		
Relay			
Male	4 × 10 km	Mass start relay with 4 athletes	Classical (Sections 1, 2) Skating (Sections 3, 4)
Female	4 × 5 km		
Sprint			
Male	1.8 km	Qualification time trial 3 sequential knock-out heats with 6 skiers in each	Classical
Female	1.3 km		
Team sprint			
Male	6 × 1.8 km	2 athletes per team perform 3 runs in alternating order; a qualifying round and final heat	Skating
Female	6 × 1.3 km		

Clearly, the distance skied (and thereby duration of exercise) vary widely; moreover, both the classical and skating techniques involve many different subtechniques. Consequently, the metabolic and muscular demands, as well as physiological responses associated with such events, also vary considerably.¹ In World Cup events, winning margins are often mere fractions of a second, and pacing strategy may well make all the difference. In this context, so-called pacing (i.e., appropriately distributing energy to prevent premature fatigue prior to the completion of the event²) is a key determinant of performance. This concept differs slightly from pacing strategy, which refers to a conscious plan for distributing effort. Abbiss and Laursen³ described 6 different pacing strategies utilized in connection with endurance performance: negative, all-out, positive, even, parabolic-shaped (e.g., U-shaped, J-shaped, or reversed J-shaped), and variable pacing. The pacing strategies in connection with XCS reported in the current review are illustrated in Fig. 1.

Generally, during endurance races, where the main goal is to regulate speed as efficiently as possible to finish as fast as possible, well-trained athletes tend to adopt a positive pacing strategy, progressively slowing down after attaining peak speed. However, the undulating terrain and various techniques involved in XCS races constitute a situation more complex than those encountered by most other endurance athletes, which influences how skiers regulate their exercise intensity and work rate (i.e., distribute their resources), as well as their pacing. Moreover, external conditions (air temperature, snow, and wind) and nutritional factors (e.g., levels of glycogen and fluid) can influence pacing during distance races. Therefore, although a variable pacing strategy may be advantageous for performances on courses where the external opposing forces vary, physiological factors related to energy production, as well as fatigue, may limit the benefits of such a strategy during XCS races.

To date, investigations of factors that influence pacing have focused primarily on individual sports. Most of these studies

have been performed under laboratory conditions, which may not reliably replicate the demands involved in actual competitions. In connection with analysis of pacing during an XCS race, variations in terrain, different racing formats (individual start, mass start, pursuit, knock-out sprint, *etc.*), effects of equipment (e.g., glide wax, grip wax, ski preparation, ski properties), and external conditions (snow, humidity, radiation, dirt, *etc.*) all present major challenges. For instance, according to regulations of the Fédération International de Ski (F.I.S.), a race track should consist of equally long uphill, flat, and downhill sections. Thus, the analysis of skiing speed (cycle velocity) or technical features (cycle characteristics, employed techniques) is only possible when multiple laps are skied on the same track or when the same section of a track is monitored repeatedly. The question is: Is there an optimal pacing strategy during XCS, irrespective of the racing format and/or distance? In addition, what is the relationship between pacing and biomechanical parameters (e.g., skiing technique), physiological parameters (e.g., aerobic capacity, strength, speed), sex and age?

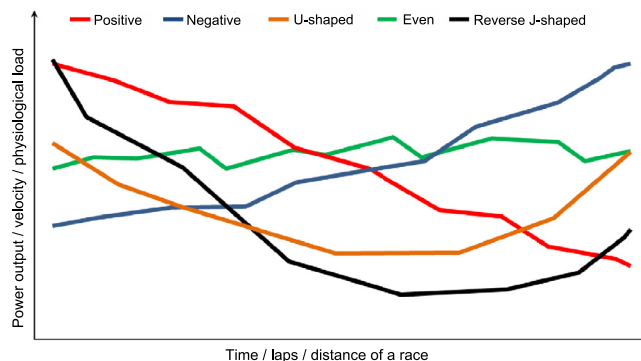


Fig. 1. Schematic illustration of reported pacing strategies applied during cross-country skiing research

Our present knowledge concerning factors that influence pacing by cross-country (XC) skiers over different distances and in connection with different types of competition is incomplete because the literature has not yet been reviewed. This review is designed to summarize what we now know and provide recommendations concerning pacing strategy and predictors of XCS race performance. It should be valuable both to athletes and coaches seeking to enhance performance in that it provides a state-of-the-art review of our knowledge concerning pacing in connection with XCS races.

2. Methods

2.1. Literature search

The PubMed, MEDLINE, and Web of Science databases were searched systematically in April 2018 to identify original research using the independent search term “cross country skiing” and the dependent terms “pacing”, “competition”, “racing”, and “race”. Reference lists of retrieved studies were also reviewed. To address our questions, we analyzed scientific articles fulfilling the following inclusion criteria: (1) the studies included formats employed in Olympic competition (e.g., from sprint to 50 km), (2) they analyzed pacing (e.g., comparison between laps, various sections of the same race, and/or sprint heats) and/or predictors of XCS performance, and (3) they analyzed actual competitions or race simulations outdoors on skis. In addition, we provided a certain amount of information concerning long-distance races (e.g., Vasaloppet and the Engadin Skimarathon), as well as research in the laboratory while roller skiing on tracks or a treadmill. In addition, only original research articles in the English language in peer-reviewed journals and available in full text were included. Journal articles were screened by title and abstract. Following an initial literature search, articles deemed appropriate on screening of title and abstract were obtained as full text and screened by the authors independently to ensure that they met the inclusion criteria. [Table 2](#) summarizes the articles meeting the inclusion criteria.

2.2. The XCS sprint

With respect to the XCS sprint, 6 articles met the inclusion criteria, only one of which involved female skiers. In addition, 5 studies were performed indoors while roller skiing on a treadmill or indoor track, and 1 study dealt with a modeling approach. Each heat distance was between 850 m and 1820 m long, with as many as 4 heats. Four of the on-snow investigations examined the classical style.

Employing 2-dimensional (2D) video analysis, Zory et al.⁴ studied 30 skiers in connection with their best lap during a 1.2 km classical World Cup race, more specifically while using the diagonal stride at the end of an uphill section approximately 200 m before the finish. In a subsequent study,^{5,6} skiers participated in a simulated classic sprint competition (1200 m, 3 heats, 12 min rest) on the 2006 Olympic track at Pragelato. This study used a 2D video recording during the last 30 m sprint with the double poling technique. Swarén and Eriksson⁷ utilized a real-time locating system (Quuppa Oy; Espoo,

Finland) to follow 70 skiers (30 females and 40 males) during the 1.4 km Scandinavian XCS classical sprint race. Stöggli et al.⁸ simulated a complete classical sprint race protocol (3 heats based on the Stockholm sprint World Cup) with roller skiing on a treadmill at self-controlled velocity and used a 2D video analysis to monitor performance and physiological (ergo spirometry, blood lactate, and heart rate (HR)) and kinematic variables during the fastest sprint. Andersson et al.⁹ analyzed 4 sprint roller skiing time trials on a treadmill, separated by 45 min intervals of rest. Each heat consisted of 3 flat (double poling) and 2 uphill (mainly diagonal stride) sections. The speed was self-paced, with a system of laser beams detecting the position of the athlete on the treadmill. Physiological parameters (oxygen uptake (VO_2), minute ventilation, blood lactate, and HR) were measured, and variables such as gross efficiency and anaerobic O_2 demand and deficit were calculated.

In the case of the skating sprint, one of the 2 field studies identified was that conducted by Andersson et al.,¹⁰ who analyzed 9 elite Swedish male XCS athletes during a 2-lap time trial (1430 m, one-third flat, one-third uphill, and one-third downhill) using a differential global navigation satellite system (GNSS) (Leica GX1230 GG; Leica Geosystems AG, Heerbrugg, Switzerland). The other field study, by Sandbakk et al.,¹¹ used 2D video to analyze 12 elite male athletes during an international F.I.S. skating sprint race (1820 m, one-third flat, one-third uphill, and one-third downhill). Vesterinen et al.¹² and Mikkola et al.¹³ examined the effect on fatigue of 4 sprints of 850 m on a flat indoor track using the V2 skating technique. Finally, Sundström et al.¹⁴ explored pacing with mathematical modeling that described the motion of a skier with a complex system of equations that took into consideration the propulsive mechanical power generated by the skier and resistive forces (i.e., the friction between the ski and snow, aerodynamic drag, and gravity). These models were designed to calculate the optimal pacing strategy for a specific athlete on a defined 1425 m hilly course.

2.3. XCS distance races

With respect to distance races, 8 publications focused on 6–15 km races in which the classic^{15–22} or skating techniques^{20–24} were used, whereas only 2 analyzed the longer distances of 30 km and 50 km.^{25,26} Four of these studies also included female skiers.^{15,16,20,21} The methodology applied included split/lap time analysis,^{17,18,21,24,25} 2D video analysis of particular sections of a race,^{16,17,19,23–26} low-cost GNSS,^{15,20} and monitoring of HR.^{20,23,25}

3. Results

3.1. Studies in the laboratory and indoors

To generate data on race performance and pacing strategies under fully standardized conditions (no effect of external conditions like snow, air, wind, or temperature) and to achieve a complex methodology (e.g., a combination of biomechanical and physiological measures), a small number of studies created race simulations using XC skiers roller skiing on a

Table 2
Summary of studies related to pacing and predictors of race performance in XCS.

Race type and author	Race format	Technique	Sex	Level of performance	Methodology and external conditions
Sprint skiing					
Zory et al. ⁴	1200 m sprint, World Cup	Classic	Male	Participants in the sprint World Cup	2D video analysis on uphill section (5%) in the fastest heat; air temperature -6.5°C , snow temperature -8.0°C
Zory et al. ^{5,6}	1200 m, 3 heats, sprint simulation	Classic	Male	Italian National Sprint Team ($\text{VO}_{2\text{max}}$: 67.1 mL/min/kg)	2D video analysis on the final flat section, average race velocity, final sprint velocity; snow temperature -9°C to -13°C , air temperature -11°C and -5°C
Andersson et al. ¹⁰	A single 1430 m time trial (2 laps), sprint simulation	Skating	Male	Swedish National Team ($n = 4$) and national-level XC skiers ($n = 5$) ($\text{VO}_{2\text{max}}$: 73.4 mL/min/kg)	Technique distribution (video), skiing velocity based on differential GNSS (Leica GX1230 GG, 20 Hz, real-time kinematic mode); clear sky, no wind, with stable air and snow temperature approximately -2°C and relative humidity 70%
Sandbakk et al. ¹¹	A single 1820 m time trial, F.I.S. sprint race	Skating	Male	12 elite XC sprint skiers ($\text{VO}_{2\text{max}}$: 70.0 mL/min/kg; F.I.S. sprint points: 44.1)	2D video analysis (10 synchronized cameras; section times) on a specific uphill section; no wind, with stable air and snow temperature -4°C and relative humidity 75%
Swarén and Eriksson ⁷	1400 m, qualification time trial & 3 heats during the Scandinavian Cup	Classic	Female and male	2 elite XC skiers	Continuous monitoring of the position of the skiers by the Quuppa real-time locating system (50 Hz)
Distance races					
Norman and Komi ¹⁹	15 km	Classic	Male	7 of the top 10 finishers and 4 of the skiers who placed 30th–60th in the 15 km 1978 Lahti World Championships	2D video analysis uphill, split times
Norman et al. ²⁶	30 km	Classic	Male	The first 5 ranked and all Canadian and American skiers in the 30 km 1988 Calgary Winter Olympics	2D video analysis uphill, split times
Bilodeau et al. ²⁵	30 km/50 km	Skating & classic	Male	Members of the Canadian National XCS Training Centers and International elite racers	2D video analysis uphill, split times, HR; snow temperature -1.0°C to -0.5°C , air temperature 1°C – 4.9°C
Rundell and McCarthy ²⁴	10 km	Skating	Female	Top US XC skiers	2D video analysis; air temperature -17°C
Welde et al. ²²	6.2 km/6.2 km	Classic & skating	Female	High-level female XC skiers ($\text{VO}_{2\text{max}}$: 67 mL/min/kg)	Ergospirometry, blood lactate concentration, HR; no wind, air temperature 2°C – 6°C
Bolger et al. ²⁰	10 km/15 km	Classic & skating	Female and male	Norwegian XCS National Team ($\text{VO}_{2\text{max}}$: 81.7 and 71.0 mL/min/kg for male and female, respectively; F.I.S. Points 4.0 and 8.0, respectively)	Low-cost GNSS coupled to Apertus inertial navigation system, HR; light wind, partly cloudy, air temperature -2°C to -5°C , and approximately 93% humidity; hard-packed mixed snow
Carlsson et al. ¹⁸	15 km	Classic	Male	Swedish and Norwegian national- to international-level XC skiers ($\text{VO}_{2\text{max}}$: 71.5 mL/min/kg)	Split time (EMIT system (EMIT eLine Base Station, EMIT AS, Oslo, Norway)); air temperature -2°C , snow temperature -3°C

(continued on next page)

Table 2 (Continued)

Race type and author	Race format	Technique	Sex	Level of performance	Methodology and external conditions
Formenti et al. ²³	10 km	Skating	Male	XC skiers from local ski teams racing at the regional to national level (VO_{2max} : 72.4 mL/min/kg)	Lap times, HR; air temperature $-9^{\circ}C$ with 70% humidity, snow temperature $-12^{\circ}C$ with 80% humidity
Losnegard et al. ²¹	10 km/15 km	Classic and skating	Female and male	Participants in the World Cup, World Championships, and Olympic Games during the 2002–2003 and 2013–2014 seasons	5 km split times (F.I.S. official race times)
Sandbakk et al. ¹⁵	10 km	Classic	Female	Elite XC skiers (VO_{2max} : 68.0 mL/min/kg)	Low-cost GNSS (Garmin Forerunner) coupled to the Apertus inertial navigation system; no wind, air temperature $-3^{\circ}C$, 93% humidity
Welde et al. ¹⁷	15 km	Classic	Male	Norwegian elite XC skiers participating in the Norwegian Championships	Split times, 2D video analysis on flat, intermediate, and uphill sections; no wind, air temperature $+1^{\circ}C$, snow temperatures of $0^{\circ}C$, humidity 86%
Stöggl et al. ¹⁶	10 km/15 km	Classic	Female and male	Norwegian elite XC skiers participating in the Norwegian Championships	Split times, 2D video analysis on flat, intermediate, uphill and steep uphill sections; no wind, air temperature $+1^{\circ}C$, snow temperatures $0^{\circ}C$, humidity 86%
Roller skiing					
Stöggl et al. ⁸	1100 m, 3 heats, on a treadmill	Classic	Male	Austrian National Sprint Team members (VO_{2max} : 64.6 mL/min/kg)	2D video analysis, VO_2 , HR, blood lactate concentration
Stöggl et al. ²⁷	1000 m, all-out maximal double poling test	Classic	Female and male	Austrian, Slovakian, and Swiss National and Student National Teams	Skiing speed during a time trial, blood lactate concentration, HR
Vesterinen et al. ¹² ; Mikkola et al. ¹³	850 m, indoor track	Skating	Male	National- and international-level Finnish XC skiers (VO_{2max} : 66.9 mL/min/kg)	30 m skiing speed determined with photo cells, heart rate, blood lactate concentration, VO_2
Andersson et al. ⁹	1300 m, 4 heats on a treadmill	Classic	Male	Well-trained XC skiers (VO_{2max} : 62.2 mL/min/kg)	VO_2 , HR, blood lactate concentration, gross efficiency, accumulated O_2 uptake and deficit
Modeling					
Sundström et al. ¹⁴	1425 m, hilly course	Skating	Male		Modeling approach
Long-distance popular races (non-Olympic distances)					
Carlsson et al. ³⁵	90 km Vasaloppet	Classic	Female and male	Both experienced and inexperienced participants of different ages	Split and race time analysis based on official timing; stable weather and track conditions (air temperature: -9 to $-1^{\circ}C$)
Nikolaidis and Knechtle ³⁴	90 km Vasaloppet	Classic	Female and male	All race finishers from 2012–2016	Split and race time analysis based on official timing
Nikolaidis and Knechtle ³³	42 km Engadin Skimarathon	Skating	Female and male	All race finishers from 1998–2016	Split and race time analysis based on official timing

Abbreviations: 2D = 2-dimensional; F.I.S. = Fédération Internationale de Ski; GNSS = global navigation satellite system; HR = heart rate; VO_2 = oxygen uptake; VO_{2max} = maximal oxygen consumption; XC = cross-country; XCS = cross-country skiing.

treadmill or indoor track. These studies focused exclusively on sprint XCS.

3.1.1. Pacing during sprint XCS as examined by roller skiing

Pacing in the laboratory or on an indoor track was examined in only 4 studies. Stöggl et al.⁸ demonstrated that sprint performance was poorer in the second than first heat but rose again in subsequent heats (although not significantly) to a level similar to that in the first heat, a so-called U-shaped pattern. Andersson et al.⁹ reported similar sprint performances in Heats 1 and 4 but slower performances in Heats 2 and 3. Of the 10 skiers examined, 5 skied fastest in Heat 1, whereas the other 5 skied fastest in the final heat. In their studies of a sprint in which athletes used the V2 skating technique on an indoor track, Vesterinen et al.¹² and Mikkola et al.¹³ found that skiing time (sprint performance), cycle characteristics, and velocity during the 4 consecutive heats were similar, with the exception of a successive reduction in starting speed. However, within each heat, the skiers utilized positive pacing and had significantly higher speed and cycle rates, along with longer poling times and swing times, during the first 50 m than in the last 50 m. This finding is in agreement with the observation by Andersson et al.,⁹ who found that 5% less time was spent on the second half of each of 4 sprint heats than on the first half. More specifically, the skiers in this study employed J-shaped pacing, with a rapid start, reduced speed on the second half of the sprint, and slight acceleration on the final section. In addition, the fastest heat was characterized by more aggressive positive pacing, with more pronounced production of anaerobic energy. Furthermore, the skiers adapted their pacing to the track profile, with an approximately 30% higher metabolic rate while skiing uphill (primarily with the diagonal stride) than on the flat sections (double poling). Finally, maximal skiing speeds (V_{\max} , determined by short ramp pretests using double poling or diagonal stride) were associated with differences in the time required to complete the first half and the second half of each sprint heat. Accordingly, the skiers with the highest V_{\max} exhibited the most aggressive positive pacing.

3.1.2. Factors correlated to roller skiing sprint performance

Four studies performed in the laboratory or on an indoor track focused on correlations between biomechanical parameters during sprint heats and overall sprint performance. The simulation by Stöggl et al.⁸ of a roller skiing sprint utilizing the classical technique on a treadmill showed that a large number of total cycles and, in particular, diagonal stride cycles, was negatively related to sprint performance ($r = -0.72$ and $r = -0.81$, respectively), and a long cycle length was positively related ($r = 0.77$), with no correlation with cycle rate. In addition, for skiing performance on the first and final uphill sections, as well as the third section of double poling, the correlations to cycle length were moderate to high ($r = 0.63$ to $r = 0.88$). The correlation between kick double poling and cycle length was low ($r = 0.59$, $p < 0.05$). Furthermore, the faster skiers employed longer and fewer total cycles throughout the race and tended to utilize double poling and kick double poling

more extensively. Strong correlations between V_{\max} ,^{8,9,27} or peak speed during a maximal anaerobic skiing test,¹³ and mean sprint performance have been reported.

3.1.3. Physiological changes during sprint skiing in the laboratory

Three investigations on physiological parameters focused on variations within or differences between heats. In one of the first studies on sprint skiing, Stöggl et al.⁸ observed significant reductions in VO_2 , lactate concentration, and tidal volume as the 3 classical sprint heats progressed. The decline in the peak lactate concentration from the first to the second heat was considered to reflect glycogen depletion and a consequent decrease in the ability to produce energy anaerobically. The fall in VO_2 was proposed to result from central or peripheral fatigue, dehydration, exercise-induced hypoxia, bronchospasm, or other mechanical limitations to respiratory flow, and inspiratory muscle fatigue might have been involved. Although the rate of breathing was unaltered, the tidal volume decreased from Heat 1 to Heat 3, which could indicate some mechanical or neuromuscular constraint on the depth of breathing.²⁸ Another possible explanation for the significantly lower VO_2 in Heats 2 and 3 compared with Heat 1 could be improvement in skiing economy, most probably as a result of adapted coordination and more economical metabolism. Particularly in Heat 3, the athletes maintained the same mean velocity with less energy expenditure, as reflected in their lower VO_2 values.

In contrast, Mikkola et al.¹³ found that, consistent with the constant mean velocity during 4 simulated sprint heats, physiological parameters such as peak oxygen uptake ($VO_{2\text{peak}}$), peak HR, and peak lactate concentration also remained unaltered. In all heats, the faster skiers exhibited higher $VO_{2\text{peak}}$ (L/min), an indicator of performance, than their slower counterparts. Andersson et al.⁹ observed no change in VO_2 , the blood lactate concentration, or rate of perceived exertion values (for breathing, legs, and arms), whereas the accumulated O_2 deficit was 14% greater during the 2 fastest heats (Heats 1 and 4). It is noteworthy that the $VO_{2\text{peak}}$ attained by each skier during each heat was similar to the maximal oxygen consumption ($VO_{2\text{max}}$) obtained during the pretests (designed specially to achieve $VO_{2\text{max}}$), and the relative contribution of anaerobic energy to total energy production during the heats was 17%–20%.

3.2. Studies on snow

In contrast to the small number of laboratory investigations, most of the reports included here analyzed skiing on snow at distances ranging from 6.2–50 km.

3.2.1. Pacing with respect to skiing speed, power output, and lap time

3.2.1.1. Sprint skiing

Comparisons between sprint heats Zory et al.^{5,6} demonstrated that the finishing time (sprint performance) and velocity profiles for repeated heats were similar, except that the

velocity during the final 30 m of each heat decreased with subsequent heats.

Analysis within a single sprint heat Within a single sprint heat, the skiers employed a positive pacing, with 2.9% slower speed on the second lap than on the first lap.¹⁰ More specifically, the athletes' skiing velocities decreased from the first to the second lap by 12.9% on the uphill sections and 5.3% on the downhill sections while increasing 7.6% on the flat sections. In addition, the skiing velocities varied most at the end of each uphill section and during the transition into the subsequent downhill section, with least variation at the end of the downhill sections, where skiing speeds were highest. Finally, the skiers with higher endurance capacity (VO_{2max}) maintained their original speed more effectively.

3.2.1.2. Distance skiing

Comparisons between laps Most investigations in this area report the use of positive pacing with respect to lap speed in connection with 10–50 km XCS races with the classical and/or skating technique. With subsequent laps, speed performance decreased 2.0%–11.8%,^{15,17,18,24,26} which was the case for both females and males.^{20,21} In addition, the fast skiers had better times on every lap, and the time difference between the fast skiers and the slow skiers was greater on the final lap than on the first lap.¹⁷ In the case of the men's 15 km races, the reduction in speed from the first lap to the third lap was higher with the classic technique (–4.4%) than with the skating technique (–4.0%), which was also the case for female skiers (–3.4% and –2.1%, respectively) (Losnegard et al.²¹). Furthermore, better skiers maintained their speed to a greater extent. Thus, the slower male skiers started more rapidly in relationship to their average speed, with a more pronounced subsequent reduction in velocity.

Only 1 study, by Formenti et al.,²³ reported a deviation from positive pacing, with all but one of the male skiers in that study employing a reverse J-shaped pacing. They skied the first 2.5 km lap more rapidly than the second and third laps (–5.3% and –7.5% slower, respectively) and then increased their speed again on Lap 4 (by 1.3% and 3.7% in comparison to Laps 2 and 3, respectively). Moreover, Bilodeau et al.²⁵ found that during a 30 km skating race, all 5 performance groups were faster on the first lap than on the second lap (with positive pacing), whereas in a 50 km classical race, the 2 best groups maintained a relatively uniform pace, with the 2 worst groups being slower on the second half of the course than on the first half. This difference reflects the greater endurance capacity of the international skiers in sustaining higher power output throughout the entire race. The slower, less experienced groups may have chosen a poorer strategy, with a fast initial pace leading to early fatigue. Because of the quite homogeneous pace of the best group, it was impossible to pinpoint exactly where the winner gained time on the others.

Changes within specific sections of a race The sectional analysis by Sandbakk et al.¹⁵ revealed that skiers lost 18 s, 6 s, and 7 s on uphill, flat, and downhill terrain from Lap 1 to Lap 2, respectively. However, pacing strategy was unrelated to overall performance, indicating that all of the skiers utilized relatively similar pacing strategies, with individual optimums

with respect to the extent of this pacing. This finding is in agreement with the demonstration by Bolger et al.²⁰ of reductions in speed on all types of terrain analyzed.

Analyzing a single uphill section only, Rundell and McCarthy²⁴ found that the skiing speed was 6.8% higher on the first lap than on the last lap. However, Welde et al.¹⁷ reported that skiers chose different pacing strategies on different types of terrain, i.e., they chose positive pacing on the flat and intermediate sections, while they chose either negative, positive or even pacing on the uphill section. The skiing velocity declined by 23.4% on the flat section, 10.6% on the intermediate incline and not at all on the uphill terrain when comparing the first lap with the third lap. Apparently, some of the skiers limited their velocity on the flatter terrain to save energy for skiing uphill.

Within the individual sections of the 2 races, Bilodeau et al.²⁵ observed differences in pacing strategy in general, as well as between the performance groups. For both the classic and skating race, uphill speed was faster in the first part than in the last part. In the case of classic skiing, the differences between performance groups were not as obvious on flatter terrain as they were on uphill terrain. For instance, the 2 best groups skied more rapidly during the first lap than during the last lap on flat terrain, while the speed of the 2 slowest groups was more constant. Therefore, the differences between performance groups with respect to skiing speed during the 50 km race are not easily explained by differences on the flat sections. When using the skating technique, all groups except the best were slower during the second lap on flat terrain.

3.2.2. Changes in biomechanical variables across a race

3.2.2.1. Sprint XCS

Only a limited number of articles dealt with changes in biomechanical parameters within and between heats of sprint skiing competitions, and none of these analyzed the kinetics of motion (e.g., pole or leg forces).

Changes between heats Zory et al.⁵ observed reductions in cycle velocity, poling time and gliding time from the first heat to the third heat. The decrease in cycle velocity was not correlated with the alterations in cycle rate and length; however, a significant negative correlation between the changes in cycle rate and length was found ($r = -0.78$), indicating that when tired, skiers who exhibited the most pronounced shortening of cycle length had the smallest decrease in cycle rate, and *vice versa*. In addition, the hip and trunk angles were larger at the end of the poling phase after the last heat, confirming that in a state of fatigue both hip flexion and inclination of the trunk are reduced. The pole angles during the middle part of the poling phase were more vertical in the third heat than in the first heat.

Changes within a single heat In the only analysis of changes in biomechanical parameters within a single sprint heat on snow, Andersson et al.¹⁰ found that skiers performed 5.2% fewer cycles of movement on the second lap, with a 5.7% lower cycle rate, 14.6% fewer gear transitions, and 6.8% and 5.9% less usage of the V2 (double dance) and V1 (single dance) techniques, respectively. The switch from the V2 to V1

skating technique on the second lap was explained by fatigue, especially in the upper body.

3.2.2.2. *Changes between laps in distance skiing*

The early investigation by Norman et al.²⁶ found no differences in any of the parameters analyzed (cycle velocity, rate, and length) from lap to lap on the steep uphill sections of the men's 30 km classical race, despite the fact that the mean speed for the second lap was slower than for the first lap. In contrast, Rundell and McCarthy²⁴ showed that the reduction in skiing speed during the women's 10 km skating race was attributed, at least in part, to decreases of 5.6%–14.4% in uphill cycle velocity by the 3 performance groups. Furthermore, the slower climbing velocity during the latter half of this race reflected an 8.5% reduction in cycle length, with no change in cycle rate.

Bilodeau et al.²⁵ demonstrated that for both the 50 km classic and 30 km skating races, faster skiers exhibited longer cycles, especially on the uphill sections, with no difference in cycle rate. On flat terrain, this same pattern was clearest when the skating technique was being utilized. Furthermore, the faster skiers maintained their longer cycles and higher cycle velocities more effectively throughout the races, and the slower skiers spent significantly more time on the uphill sections than on the flat sections. The attenuated uphill velocities on the second lap when skating were explained by shorter cycles, because the cycle rates on these laps did not differ among the performance groups. In the case of classic skiing, the skiers elevated their speed on the flat terrain of the final sprint by enhancing cycle rate and shortening cycles.

Welde et al.¹⁷ found that the Norwegian athletes in their study skied with 11.8% slower cycle velocity and 11.7% shorter cycles on the final lap than on the first lap. As with the cycle velocity, the cycle length declined most on flat terrain (–19.6%), followed by intermediate terrain (–10.8%), and then uphill sections (–4.8%). In contrast to the studies described earlier, cycle rate also changed during the 15 km race, decreasing 3.4% on flat terrain and increasing 4.0% uphill, with no change on intermediate terrain. Furthermore, the elite male skiers employed double poling and kick double poling to a greater extent during the first half of the 15 km race, switching to more extensive kick double poling during the second half, whereas the slower skiers did the opposite.

3.2.3. *Correlations between race kinematics and overall race performance*

3.2.3.1. *Sprint XCS*

Sandbakk et al.¹¹ and Andersson et al.¹⁰ showed that sprint skating performance on the uphill ($r = 0.91$ and $r = 0.92$, respectively) and flat sections ($r = 0.82$ and $r = 0.75$, respectively) of a race were related to overall performance, whereas downhill performance was not or revealed only a trend ($r = 0.60$). In the study of Sandbakk et al.,¹¹ the starting speed on the initial flat section and the first part of the first uphill section were not related. This indicates that the time required to attain high

speed from standing still and downhill performance may be similar for different elite male skiers and that different pacing strategies are applied. Furthermore, the longer cycles on the uphill section in the middle of the sprint were associated with more rapid uphill skiing, whereas cycle rate demonstrated no such correlation.

Andersson et al.¹⁰ reported that the percentage of time spent using the V1 skating technique was negatively associated with race velocity ($r = -0.72$) and positively with F.I.S. points ($r = 0.71$). Furthermore, the magnitude in the change in gear distribution on the uphill section from the first lap to the second lap tended to show a negative correlation to skiing velocity. The more extensive usage of V2 uphill is reflected in the negative correlation between the velocity when transitioning from flat to uphill terrain and the percentage utilization of V1 ($r = -0.81$ and -0.90 for Lap 1 and Lap 2, respectively). In other words, the faster skiers utilized V2 more than V1, with the fastest skier using the V2 technique exclusively along the entire track.

3.2.3.2. *Distance skiing*

In most cases, better performance in the 10–50 km races, irrespective of sex and technique, was related positively to more rapid cycle velocity and/or longer cycles on flat,^{15,16,19,20,25,29} intermediate,^{16,17} and uphill terrain.^{15,16,19,20,24–26} In contrast, cycle rate on any type of terrain demonstrated almost universally no association with race performance.^{24–26,29} The exception to this was the finding by Norman and Komi,¹⁹ who found a lower cycle rate on flat terrain and a higher cycle rate on uphill sections by the faster skiers. The latter observation is in agreement with Stöggl et al.,¹⁶ who found that on steep and very steep uphill terrain, cycle rate was related to the race performance of female skiers. Moreover, the 3 fastest male skiers employed both longer cycles and a higher cycle rate than all of the other skiers. In 2 reports, skiing velocity downhill was also found to be associated with distance race performance.^{15,20}

In summary, the contributions of skiing velocities on uphill, flat, and downhill terrain to overall distance skiing performance are quite different. This is reinforced by the fact that, in general, >50% of the total time during XCS distance races is spent skiing uphill, and uphill performance is consequently regarded as the major determinant of success.^{15,19,20,25,30,31}

Stöggl et al.¹⁶ observed that on intermediate terrain, the male skiers employed double poling and kick double poling to a greater extent than the female skiers, who primarily utilized kick double poling and the diagonal stride and performed more transitions. Furthermore, faster skiers employed kick double poling to a greater extent and diagonal stride to a lesser extent than the slower skiers, with approximately equal usage of double poling. This finding is in line with recent findings on the performance of male skiers during the first half vs. the second half of a 15 km classical XCS race.¹⁷

3.2.4. *Physiological responses during a race*

In contrast to the numerous studies on skiing speed and biomechanical parameters during XCS races, few investigations have focused on physiological changes during a race or

between sprint heats, especially with regard to pacing. The only 3 articles of this nature on sprint skiing did not involve skiing on snow but rather roller skiing indoors.^{8,9,13}

3.2.4.1. Distance XCS races

Norman et al.²⁶ estimated that on the uphill sections of a 30 km classic race, many skiers perform at an intensity greater than their $\text{VO}_{2\text{max}}$ and then utilize downhill sections for recovery. They found VO_2 values of 80–112 mL/kg/min for the faster skiers on most laps, whereas the corresponding values for the slower skiers were 53–77 mL/kg/min. Judging from HR, Bilodeau et al.²⁵ concluded that a selected group of skiers demonstrated a similar level of physical exertion on both laps of 30 km skating and 50 km classic races. During the 30 km skating race, the skiers' HR was slightly higher going uphill (183–185 bpm) than on flat terrain (173–174 bpm), with only a limited difference in the case of the 50 km classic race (i.e., the skiers had higher HR on the last flat part of the finishing sprint).

Welde et al.²² reported systematic changes in the physiological output in response to alterations in the terrain, with no effect from the technique utilized. During this race, the highest VO_2 (95% of $\text{VO}_{2\text{max}}$) and HR (97% of maximal HR (HR_{max})) were detected at the end of a long uphill section, whereas the highest blood lactate concentrations (classical skiing: 10.5 mmol/L; skating: 9.1 mmol/L) occurred at the end of the race.

Formenti et al.²³ reported that the mean HR during a 10 km race was approximately 91% of HR_{max} , with the HR being >90% of maximal during 67% of the total race time and 80%–90% of maximal the remainder of the time. Bilodeau et al.²⁵ reported a progressive increase in intensity, with a 2.4% higher HR during the last lap than during the first lap of the race. It is worth noting that potential associations between race performance and the alterations in HR or the distribution of intensity across a race were not yet examined. The increase in HR during the second lap was proposed to reflect cardiovascular drift, resulting in a reduction in stroke volume.³²

In addition, Bolger et al.²⁰ detected no relationships for either males or females between the relative HR (% HR_{max}) and aspects of pacing, such as speed within the sections analyzed and race performance with the skating or classic techniques. Thus, the significant changes in kinematic variables (e.g., cycle velocity, lap speed, and cycle length) during races of various distances were not reflected in the alterations in HR. The relative paucity of studies on the physiology of XCS racing limits our understanding in this area.

3.2.5. The influence of sex, anthropometric characteristics, and age

3.2.5.1. Sprint skiing

In the only comparison of sprint skiing by males and females known to us, Swarén and Eriksson⁷ found that in the first 20 m of the final race, the average propulsive power for the 1 female skier analyzed was 11% higher than in the

qualification heat (345 W vs. 308 W, respectively), whereas for the 1 male skier this power was 17% lower (356 W vs. 430 W, respectively). The pattern for the final spurt was the same, with higher values than in the qualification heat for the female (380 W vs. 361 W, respectively), and lower for the male (411 W vs. 475 W, respectively). Unfortunately, this comparison involved only 2 skiers, and the potential underlying mechanisms were not discussed in detail.

3.2.5.2. Distance skiing

Carlsson et al.¹⁸ observed an increase of approximately 1% in lap speed with every 1 year increase in a skier's age, indicating that older skiers may utilize a more optimal pacing, although physiological and technical factors, such as better gross efficiency and skiing economy, might also be involved. Furthermore, skiers who weighed more exhibited a more pronounced positive pacing profile than lighter skiers, apparently because of the heavier skiers' greater muscle mass, which gives them superior ability in generating a high skiing speed and thereby allows them to take a leading position at the beginning of the race. In contrast, lighter skiers have an advantage in connection with ascents. Thus, during the latter part of a distance race, lighter skiers are in favor during the later parts of a distance race when the time spent skiing uphill increases, caused by an overall reduction in skiing speed (see earlier discussion). Accordingly, pacing appears to be influenced by body mass, with heavy skiers potentially benefitting from a somewhat reduced speed during the first part of a distance race.

Direct comparisons between female and male with respect to pacing are rare. As described previously, Losnegard et al.²¹ demonstrated that both sexes employ positive pacing with both skating and classical techniques. The speed of the fastest male skiers declined less than that of their slower counterparts, whereas female skiers with different levels of performance exhibited similar pacing strategies. For the females, mean race velocity was more consistently correlated with performance on the first lap (mean $r = 0.95$) than was the case for the males (mean $r = 0.74$). Stöggl et al.¹⁶ found that the largest absolute sex differences in cycle velocity and cycle length were observed while skiing on flat terrain. This result is also strengthened by the fact that for the males, skiing velocity on the flat section was highest related to race outcome, whereas for the females, this was the case for the skiing velocity in the uphill section.

3.2.5.3. Long-distance skiing

For long-distance popular races (e.g., the 90 km Vasaloppet with classical skiing and the 42 km Engadin Skimarathon with skating), the currently available research on pacing and physiological response is limited. Nikolaidis and Knechtle^{33,34} found that in both of these races, the males demonstrated more even pacing than the females. Furthermore, young participants employed more even pacing than older ones during the Skimarathon race, with no such differences found for the Vasaloppet race. In contrast to that, among a relatively small sample of finishers in the Vasaloppet race, the females

exhibited more even pacing than males with the same finishing time, start group, age, and racing experience. Furthermore, although the males were faster during the first half of the race, the females were faster during the second half. Moreover, experienced skiers skied faster during the first half (positive pacing), whereas inexperienced skiers showed higher speed during the second half (negative pacing).³⁵ At present, the physiological responses or biomechanical output during long-distance skiing remain to be analyzed.

4. Discussion

This review has strived to identify the different pacing strategies and predictors of performance in connection with XCS competitions in Olympic distances. The major findings were as follows: (1) in most studies, positive pacing (i.e., a continuous decline in skiing velocity as the race progresses) was observed irrespective of distance, technique, or sex; (2) pacing by better skiers (e.g., with higher aerobic capacity) tended to be more even, whereas skiers with a lower level of performance and/or experience exhibited more pronounced positive pacing; (3) performance and level of strength are linked to the usage and selection of technique, especially on uphill terrain (e.g., more extensive utilization of double poling and kick double poling, or of V2 instead of V1); (4) cycle length was the main determinant of cycle velocity and race performance on various types of terrain, whereas in most cases the cycle rate was unrelated; and (5) uphill performance was more closely related to overall performance of female skiers, whereas performance on flat terrain, followed by intermediate and uphill terrain, was more decisive for the male skiers. The main findings are summarized in Fig. 2.

A substantial number of investigations have documented pacing strategies applied during real or simulated XCS races in relationship to performance. In contrast, to date there has been no systematic analysis of the influence of different pacing

strategies on performance, based on modern physiological and biomechanical measurements and taking into consideration potential confounders, such as changes in the glide and/or grip properties of skis. In this context, it is noteworthy that on applying mathematical modeling to a world-class male XCS sprinter, Sundström et al.¹⁴ found variable pacing (i.e., striving to enhance propulsive power when skiing uphill and reducing this power on the downhill slopes, all the while trying to maintain as constant a speed as possible) to be optimal, saving as much as 13 s, or 6.5%, of the total time in comparison to even pacing. In contrast, most studies on actual races have observed usage of positive pacing (e.g., higher initial skiing speed with a steady decrease thereafter).

The ability to achieve and maintain long cycles on all types of terrain was necessary for success in all cases, whereas cycle rate consistently lacked any association with performance. Recent reports indicate, however, that better XC skiers (both female and male) can ski with both longer cycles and higher cycle rates on moderate-to-steep uphill terrain. Cycle length is linked to technical features of skiing (e.g., forward lean at the moment of pole plant, dynamic use of the lower body to attain a high position prior to the pole plant) and the magnitude of the propulsive force impulses (by legs and poles). Propulsion is, in turn, related to the general and specific strength of the athlete and appropriate coordination of the force applied during the propulsive phase (e.g., high resultant forces at an angle more optimal with respect to the direction of skiing).^{36–40} In this context, it was recently demonstrated that classical skiing techniques involving longer cycles, more well-timed application of force, and prolonged ground contact were linked to increased extraction of O₂. The opposite pattern was proposed to produce mechanical hindrance of some undefined nature to O₂ extraction (and potentially to blood flow and perfusion as well).^{41,42}

In general, performance uphill was closely related to overall race performance, although recent evidence indicates that

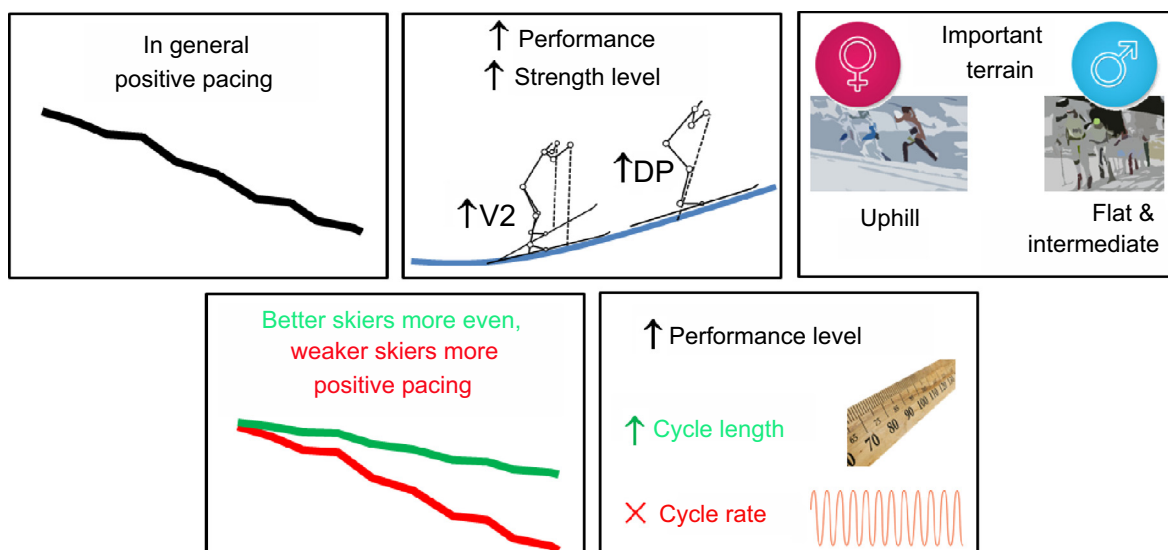


Fig. 2. Summary of the main findings based upon the literature review on pacing in cross-country skiing. DP = double poling; V2 = V2 skating technique.

while this is true for female skiers, performance on flat terrain is of greater significance for male skiers. Pacing was also coupled to the extent to which and where different skiing techniques were employed during a race. On the intermediate terrain of a 10 or 15 km race, faster skiers utilize more double poling and kick double poling and less diagonal stride, whereas in the case of sprint XCS skating, better performance was associated with enhanced usage of the V2 rather than the V1 technique, as well as maintenance of V2 during both laps of a heat. Enhanced application of these 3 more advantageous techniques is strongly influenced by the technical skills and upper body capacity (aerobic capacity, strength, core stability, *etc.*) of the skier.

Researchers in this field propose that the distribution of speed during various forms of exercise is regulated, at least partially, on a subconscious level⁴³ in a manner that may differ from what the athlete aims for consciously. In response to complex peripheral feedback and central drives, energy expenditure is adjusted continuously, both consciously and subconsciously, in an attempt to maintain physiological homeostasis (or acceptable deviations from this status), as well as to delay the effects of fatigue.³ The more recent concept of “pacing awareness”⁴⁴ proposes that in addition to such conscious and subconscious adjustments, the individual’s state of awareness exerts a considerable impact on energy expenditure. For instance, minor corrections required to maintain homeostasis involve little or no awareness, whereas the management of strenuous activities that cause large disturbances in metabolism, such as depletion of glycogen, requires more awareness. Since the metabolic demands made by the various types of XCS races differ, the levels of subconscious and conscious awareness necessary for optimal performance are probably dissimilar as well. However, none of the articles on XCS examined here took such factors into consideration.

Moreover, potential changes in external conditions or in the physical properties of skis during a race are not mentioned in any of the studies covered here, and consequently, the differences in pacing strategy cannot be definitively explained. Such changes might lead to the more pronounced variation in the classical XCS races, where both glide and grip wax are applied, and might become less effective as the race proceeds (e.g., owing to contamination and/or loss of ski base structure or the wax itself), thereby elevating ski-snow friction. Indeed, so-called positive pacing might simply reflect such changes. Clearly, the possibility of changing skis during longer races (in connection with pit stops), introduced recently, complicates the situation even more. Furthermore, the effects of nutrition on pacing during longer XCS races (e.g., 30 km and 50 km) remain totally unknown.

A substantial number of articles make comparisons between multiple laps, whereas only a few analyze different sections, or the whole, of the same race (e.g., with GNSS or inertial measurement units). When comparing laps, one must be aware of the substantial changes that have occurred across the decades. For example, XCS laps used to be quite long in former times (e.g., 10.0–12.5 km), but in today’s racing formats, they are mostly only 2.5–5.0 km in length. In

connection with such comparisons, it is also important that all of the laps are of the same length. For instance, the separate start and finishing corridors present in most races might result in differences in lap length. Another disadvantage of simply comparing laps is that details concerning the various sections (usually equal lengths of uphill, flat, and downhill terrain) of a race are missed. Sectional analysis (e.g., by video recording) can provide such information (e.g., Stöggl et al.¹⁶ and Welde et al.¹⁷), and improvements in the accuracy and size of modern differential GNSS and/or real-time locating systems^{7, 45} might facilitate and enhance the quality of analyses of XCS pacing. Whereas extensive data concerning biomechanical XCS parameters such as speed and cycle velocity, section time, and cycle characteristics in relationship to pacing and race performance are available, information concerning physiological response during a XCS race is much more limited. In addition, there are no reports on potential alterations in kinetics (e.g., changes in pole and/or leg forces) during XCS. Finally, most reports to date have involved laboratory conditions, which may not reliably reflect the demands made by actual competition. In connection with the Olympic Games in Beijing in 2024, it would be of considerable interest to use a fixed local positioning system together with miniaturized rovers, inertial measurement units, and sophisticated algorithms to monitor and, possibly, share various biomechanical parameters (e.g., power output, forces, cycle characteristics, and effectiveness) and physiological parameters (HR, near-infrared spectroscopy, *etc.*) with spectators.

From a historical perspective, racing formats have also changed substantially. The more classic studies focused primarily on individual starts; however, modern XCS races encompass a much wider variety of formats, including the mass start, pursuit, knock-out sprint, time trial, team sprint, and so forth. With a mass start (involving drafting and possible tactical considerations), pacing strategies might differ substantially from those employed in connection with an individual start. To the best of our knowledge, these aspects of XCS remain to be examined.

Furthermore, coaches must think about how and when feedback about time should be given to the athlete during competition. With sprint skiing, it might be important to take entrance velocity during a qualification heat into consideration, but in this case the literature presently available provides no basis for recommendations concerning the optimal pacing strategy (e.g., even, positive, negative, J-shaped, reversed J-shaped, or U-shaped). It is worth mentioning here that feedback might also be of value from a physiological/psychological perspective. For example, skiers tend to start fast to achieve favorable early position, and initial negative pacing might lead to an early position that is demoralizing. With a mass start, information concerning time is not as crucial; those in the leading group simply need to know that they are ahead, and the followers need to know how far behind they are. In this context, the potential effects of external encouragement by spectators/fans should also be taken into consideration. Most spectators usually stand near the start and finish of a race, which could have

consequences for skiing speed that are to date totally unexplored.

Numerous studies have analyzed sex differences with respect to skiing performance on various sections of a track and the application of different skiing techniques, but only a few have compared the pacing strategies employed by female and male skiers.²¹ In the case of sprint skiing, a single case study has compared 1 female skier with 1 male skier,⁷ and comparisons over long distances (e.g., 30 km for females and 50 km for males) are totally lacking. There are differences between females and males with respect to pacing strategies. For example, analysis of the 15 km Olympic race by Losnegard et al.²¹ revealed that the fastest males demonstrated less pronounced positive pacing than their slower competitors, whereas the females at all levels of performance demonstrated similar positive pacing. In connection with the long-distance popular races, either the pacing by males was more even than that by the females^{33,34} or *vice versa*.³⁵ Therefore, future research should focus not only on the effectiveness of different pacing strategies but also on sex and, possibly, age and racing experience in this context.

5. Conclusion

Most of the publications reviewed here describe a positive pacing strategy (i.e., a steady decrease in skiing speed as the race proceeds), irrespective of race format, skiing technique, and/or sex. However, some findings indicate that higher-level athletes and those with greater endurance and strength can utilize more even pacing, whereas lower-level skiers and/or those with less racing experience can employ more pronounced positive pacing. The ability to achieve and maintain long cycles on all types of terrain was necessary for success in all cases, whereas cycle rate consistently lacked any association with performance. In general, performance uphill was closely related to overall race performance, more so for female skiers, with performance on flat terrain being more important for the males. In addition, pacing influenced the extent to which, as well as where, different skiing techniques were utilized during a race, with faster skiers employing more double poling and kick double poling and less diagonal stride, or more of the V2 than V1 technique during sprint skiing.

The enhanced understanding provided by this review of pacing strategy and of the selection and biomechanics of the different classical skiing techniques on various types of terrain, as well as of the relationship between a skier's performance on sections of a race and his or her overall performance, has practical implications. We propose that skiers at all levels can improve their performance with more specific training related to technique (i.e., training designed to help the athlete maintain long cycles without compromising cycle rate), on different inclines, at different speeds, and under varying external conditions, in combination with training for endurance and, if necessary, more strength. Furthermore, we would advise less experienced skiers and/or those with a lower level of performance to apply a more

even pacing strategy rather than a positive one (i.e., to start the race fast).

These conclusions are somewhat tentative, because none of the studies controlled for the effects of potential changes in external conditions (e.g., snow characteristics, properties of the glide and grip waxes, accumulation of dirt at the base of the ski, changes in the quality of the track) or intrarace nutritional strategies (e.g., carbohydrate or fluid intake). Therefore, the relative impact of factors related to the individual skier (endurance, strength and speed, race tactics, psychological factors) vs. the impact of external factors on pacing strategy and race performance are not yet clear. Furthermore, another limitation is that none of the studies analyzed the influence of different pacing strategies with an experimental approach. Future experimental investigations should take potential changes in external conditions during measurements into consideration, as well as apply state-of-the-art technologies (e.g., miniaturized and wireless systems like high-end GNSS, inertial measurement units, near-infrared spectroscopy, and portable VO₂ monitors) for both biomechanical and psychophysiological monitoring, with a special focus on field studies that cover on-snow races and female skiers.

Authors' contributions

TS conceived of this study, planned the organization of the manuscript, searched and reviewed the literature, wrote the manuscript, and designed the tables and figures; BP and H-CH reviewed the first and final versions of the manuscript. All 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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