Sport Sciences for Health
https://doi.org/10.1007/s11332-024-01199-4

RESEARCH

Ski-orienteering: a scientific perspective on a multi-dimensional challenge

Jonatan Ståhl[1] · Roland Larsson[2] · Hans-Christer Holmberg[3,4]

Received: 9 September 2023 / Accepted: 22 March 2024

Abstract

Ski-orienteering, which combines cross-country skiing with orienteering, dates back to the late 1800s, with the first World Championships in 1975. While researchers have explored the physiological and biomechanical determinants of success in cross-country skiing and orienteering separately in detail, scientific knowledge concerning ski-orienteering remains limited. Based on the information that is presently available together with interviews with elite ski-orienteers, we explore here for the first time the historical development, physiological, biomechanical, and psychological demands, certain training strategies, and future prospects and challenges associated with this sport, including its potential to become an Olympic event. A demanding endurance sport (with racing times of 12–120 min), ski-orienteering requires both considerable aerobic and anaerobic capacity, as well as well-trained upper and lower body muscles. In addition, ski-orienteering demands advanced skiing technique on various types of terrain, with frequent changes between sub-techniques, on both wide and narrow tracks and with numerous turns on downhill terrain. Moreover, success in this sport requires accurate and rapid orienteering—the ability to navigate a complex network of ski tracks with numerous intersections/crossings in a manner designed to pass the multiple control points in the order indicated on the map as rapidly as possible, i.e., advanced spatial cognition and highly developed navigational skills. Thus, ski-orienteering requires training designed to improve both relevant physiological characteristics and orienteering skills, which should become the focus of future interdisciplinary research on this complex sport.

Keywords Cognitive fatigue · Cross-country skiing · Decision-making · Map reading · Navigation · Performance

Introduction

Ski-orienteering, an endurance sport that combines cross-country skiing and orienteering over a large network of tracks, is uniquely challenging [1]. In addition to requiring optimal development of relevant physiological characteristics, this sport requires intense focus on choosing the shortest and/or most rapid route to ski, even when stressed and exhausted. Furthermore, while skiing on narrow tracks on challenging terrain covered with snow of varying properties, the ski-orienteer must transition smoothly between a variety of sub-techniques that involve the upper and/or lower body muscles to different relative extents. In this perspective article, we present a brief overview of the history and organization of ski-orienteering, as well as highlight current advances and suggest avenues for future development. A thorough search of the literature (completed in December of 2023) covered by PubMed and Web of Science, revealed no previous scientific articles exploring the sport of ski-orienteering.

Based on the information that is presently available together with interviews with elite ski-orienteers, we explore here for the first time the historical development, physiological, biomechanical, and psychological demands, certain training strategies, and future prospects and challenges associated with this sport, including its potential to become an Olympic event.

✉ Hans-Christer Holmberg
integrativephysiobiomech@gmail.com

1 Umeå Orienteering Development Centre, Umeå University, 901 87, Umeå, Sweden

2 Division of Machine Elements, Luleå University of Technology, 971 87, Luleå, Sweden

3 Department of Health Sciences, Luleå University of Technology, 971 87, Luleå, Sweden

4 CeRiSM, Sport Mountain and Health Research Centre, University of Verona, Rovereto, Italy

The history and evolution of ski-orienteering

Although the first known public ski-orienteering competition was held as early as 1887 in Sundsvall, Sweden, it was not until 1975 that the International Orienteering Federation (IOF) recognized this sport, with the first World Ski-Orienteering Championships being held in Finland that same year [2]. Since then, the number of national and international events has been increasing steadily and, at present, about 15 nations participate in international ski-orienteering competitions [3].

The first six World Championships involved only an individual race (with a winning time of approximately 90–120 min) and a relay involving four ski-orienteers. In 1988, a short-distance event (with a winning time of 30–45 min) was added and in 2002, the Sprint event, with a winning time of 12–15 min, was also included, leading to the short-distance event being lengthened somewhat and redesignated as middle-distance. At the 2005 World Championships, the relay was reduced from four to three legs and in 2011 the Sprint Relay, in which one man and one woman each ski three relatively short sections, was introduced. The current World Championship program includes the Sprint, Pursuit, Middle Distance and Sprint Relay (Table 1), while the other events shown in Table 1 are included in other World Cup and European Championship competitions [1].

Indeed, ski-orienteering is included in several major international multisport events. It has been a part of the Asian Winter Games since 2011 and the Winter Universiade (World University Games), where it debuted in 2019 and will become compulsory in 2027 [4, 5]. Ski-orienteering is also featured in the Conseil International du Sport Militaire (CISM) World Military Winter Games [4, 6]. In addition, the International Orienteering Federation has made several, as yet been unsuccessful attempts to include ski-orienteering in the Winter Olympic Games (2014 and 2018) [4, 7].

The basics of ski-orienteering

Ski-orienteering takes place in natural environments including, e.g., forests, hills, and mires. The competition is usually performed on a network of wide ski tracks, most often including a stadium or arena, built for competitions in cross-country skiing and/or the biathlon in combination with narrower ski tracks prepared by the organizers for that specific competition [1]. The entire network consists of 50–100 km of groomed ski tracks that vary in width, including 20–50% of cross-country ski tracks/trails (often prepared with a piste machine) > 2 m wide that allow higher speed and 50–80 km of 0.8–1.2-m-wide tracks/trails (made with a snowmobile, here referred to as narrow tracks) [8]. The start, finish, map changes, and, in the case of relays, changeovers typically occur in the arena. Following announcement of the area for competition, no competitor or coach is allowed to enter this area, so the terrain remains unknown.

A ski-orienteer uses the same equipment as a cross-country skier, including boots, bindings, and skis for the skating technique (Fig. 1) [8, 9]. Although most athletes also use ski poles similar in length to those employed for skating in cross-country skiing, some utilize slightly shorter poles to facilitate double poling on narrower tracks. In all cases, the pole basket diameters are as much as threefold larger than those on cross-country skiing poles, which prevents the pole from penetrating deep into the relatively soft snow beside the narrow tracks.

To enable the skier to view the map clearly while skiing, a holder attached to the chest positions the map in front of the face. Most of these athletes also carry a compass fastened to the map-holder or wrist, for help in navigating certain situations. For an experienced ski-orienteer, the compass is less essential than in the case of orienteering on foot. In addition, the skier has a wireless electronic timing chip on a finger or wrist for registering arrival at each control point.

The map, showing all of the control points to be passed as rapidly as possible in the sequence indicated (Fig. 2), is

Table 1 The ski-orienteering events currently included in the World and European Championships and in the World Cup for Ski-Orienteering

Events on the international program	Estimated winning time (min)	Course length (linear distance in km)	Approximate actual skiing distance (km)	Number of controls[a]
Sprint race	12–15	3–4	3.5–5	10–15
Middle distance race	40–45	7–10	10–15	20–25
Long distance race	85–95	15–25	20–30	25–35
Mass-start race	50–60	10–15	13–20	30–40
Pursuit race	50–60	10–15	13–20	30–40
Sprint relay (6 legs, 2 athletes)	6–8 min/leg	1.5–2.5	2–3	8–12
Relay (3 legs, 3 athletes)	30–35 min/leg	6–8	8–12	15–20

[a]These controls are described in more detail in "The basics of ski-orienteering"

Fig. 1 An elite male ski-orienteer equipped with his standard racing gear for competing at the Ski-Orienteering World Championships in 2021. A device holds the map 15–30 cm in front of his face. At the same time, an electronic unit for marking each control as he passes needs only to be within 30 cm from the control to do so, as a result of which the athlete does not have to stop completely at controls (although controls located on a downhill slope require greater reduction in speed)

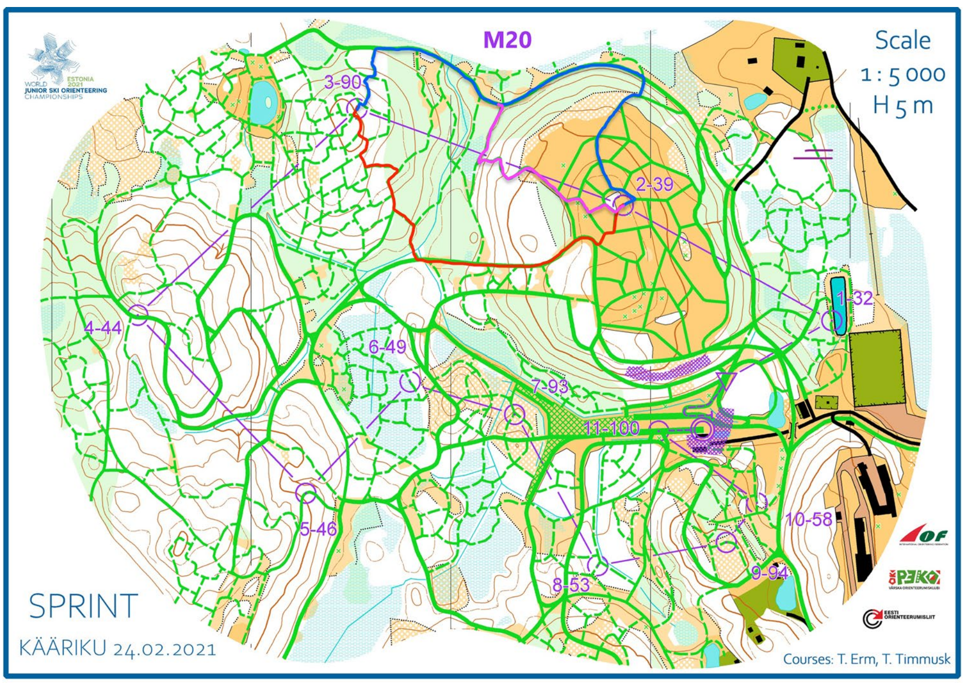

Fig. 2 A map of a ski-orienteering course prepared for the 2021 Junior World Ski-Orienteering Cup in Kääriku, Estonia, illustrating the characteristic, slightly hilly Baltic forest terrain along with some open areas and marshes. White indicates normal forest, light green more dense forest, yellow open areas, and blue mires or water. The prepared ski tracks are shown in green, with the solid lines depicting normal tracks > 2 m in width and the dashed lines tracks approximately 80–120 cm wide. The purple line depicts the course, where the start is the triangle (which has one corner pointed towards the first control), the controls are circles, and the finish a double circle. The first digit of the control marker (e.g., 1–32) indicates the sequential number of the control and the second digit(s) ((e.g., 1–32) the number to be used in connection with the electronic punching. We have constructed three possible routes from control 2 to control 3 in blue, pink and red

given to the skier only 15 s before the start of the race [8]. This map also provides information about the network of tracks and features of the terrain, such as hills, vegetation, open areas, houses, roads, frozen or thawed bogs/lakes. etc., thereby aiding the skier in deciding which route would be fastest in light of his individual strengths and weaknesses.

In the case of relays, when the members of the team ski successively after one another, the first skier receives the map 15 s prior to the start, while the others receive the map in connection with the change-over they are involved in. As also is the case for individual races with mass or chase starts, the courses are branched, with somewhat different controls, so that skiers/teams cannot simply follow one another. In this way, each member follows a slightly different course, although all teams visit the same controls. There is usually no communication between the team members during a race—there is no time to communicate during changeovers and, moreover, a team member who has finished their leg is not allowed to communicate with a team member who has yet to start.

The physiological demands of ski-orienteering

Ski-orienteering is a demanding endurance sport, involving, as indicated above, competitions of different lengths on varying terrain employing different combinations of upper and/or lower body work. The physiological factors that could potentially limit overall performance include aerobic capacity (which is required to maintain speed, proper technique, and mental focus), anaerobic capacity (required when energy demands are especially great, as when skiing on steep uphill terrain, as well when sprinting towards the finish), muscular strength (especially in the upper-body, including the core), balance, coordination and agility (particularly when skiing on narrow tracks, on technically difficult downhill terrain, and/or through narrow sections of the course).

All in all, the physiological demands associated with ski-orienteering are comparable to those placed on cross-country skiers [10, 11]. In both cases more than 50% of the racing time is spent skiing uphill, the sections where inter-individual performance varies most. The best ski-orienteers are well-trained endurance athletes, highly skilled at skiing, and, indeed, in certain cases, capable of competing well against elite cross-country skiers at the national level [12].

World-class cross-country skiers exhibit some of the highest maximal oxygen uptake (VO_2 max) values ever reported [10, 13–15], i.e., 80–90 and 70–80 mL kg^{-1} min^{-1} for men and women, respectively. The corresponding values for ski-orienteers competing at the international level range from 70 to 75 and 60 to 65 mL kg^{-1} min^{-1} for men and women, respectively, with utilization of > 90% of their VO_2 max when employing the double poling technique (based on interviews with our ski-orienteers). In ski-orienteering, more skillful orienteering and skiing technique may compensate for less-than-optimal aerobic capacity, but only to a certain extent.

Pacing in individual cross-country skiing and biathlon races is regulated primarily by the skiers themselves. In contrast, the specific challenges associated with ski-orienteering demand strategic adjustments in pacing. For example, skiing steep uphill segments on narrow tracks requires extra effort, making it necessary to recover on subsequent sections to avoid excessive fatigue.

Biomechanical aspects of ski-orienteering

In addition to the factors discussed above, successful ski-orienteers require the ability to alternate between the different skiing sub-techniques on both wide and narrow tracks and in response to the changes in speed and incline encountered along the course. The technical complexity involved in distributing the generation of force between the upper and lower body muscles in an optimal manner presents both opportunities and challenges. Maximal skiing speed exerts a greater effect on overall performance in the pursuit, mass-start races, and relays, where a rapid finish is required, than in individual start ski-orienteering events.

From a biomechanical perspective, ski-orienteers resemble cross-country skiers, employing a wide range of speeds over varying terrain with frequent transitions between the different sub-techniques (also referred to as gears), as well as utilizing different downhill and turning techniques (for an overview and definitions, see Table 2) [16]. The many transitions between gears must be chosen and timed properly for the prevailing terrain and track conditions (including track width) and, in addition, require mastery of the various skating and double poling sub-techniques. Moreover, a ski-orienteer needs to frequently adjust his/her power output and cycle length in response to changes in conditions. On soft tracks with lower poling force, the poling frequency will likely be higher and cycle length shorter to avoid penetrating through the snow and thereby losing energy.

At the same time, unlike cross-country skiers, ski-orienteers must read the map and choose the optimal route for skiing. The mental focus required varies at different points along the course and may be so great as to slow down the skier's speed. On the wider sections of the course, the skiers generally ski considerably faster, accumulating fatigue from which they may recover on other sections of the track, especially downhill portions.

Table 2 The various skiing techniques utilized in ski-orienteering (Ski-O)

	Description of the specific sub-technique	Description of where this sub-technique is utilized in Ski-O
Skating gear 1	A skating version of the diagonal stride technique of classical skiing, in which the diagonal leg and arm perform a single pole-push in combination with a skating-like push by the other leg	Utilized on narrow uphill tracks too steep for double poling. The skier must make sure that the tip of the skis does not plough into the loose snow alongside the track
Skating gear 2	This asymmetrical technique involves a single asymmetrical double-pole push in combination with every second leg-push	Utilized on wide tracks on increasingly steep uphill terrain, as well as occasionally to counteract friction and accelerate on moderate terrain
Skating gear 3	With this gear, a single double-pole push is performed together with every leg push	Utilized on wide tracks on flat-to-moderately steep uphill terrain, as well as during the finishing spurt
Skating gear 4	This involves use of the arms and legs in the same manner as with gear 2 technique, but without any pronounced asymmetry	Utilized primarily on wide tracks on flat or slightly downhill terrain, when glide is good and skiing speed high
Skating gear 5	Here, only the legs are used, while the arms remain stationary or move alongside the trunk	Used on slightly downhill terrain and under other conditions when the speed is so high that poling cannot be performed effectively
Double poling	Only the arms are used symmetrically and in parallel together with the upper body, as the skis glide parallel to one another	Utilized on tracks too narrow to allow skating, on anywhere from slightly downhill to steep uphill terrain
One-legged skating	This technique involves double poling while loading the body weight onto only one ski and pushing outwards in a skating-like fashion with the other ski	Utilized on tracks to complement double poling where there is sufficient space, during turns and when the track tilts
Step turning	Step turning is initiated by lifting the inner ski while pushing off with the extended outer leg, with or without poling	To maintain or increase speed while turning
Snow ploughing	By placing the skis in a reverse V-formation and lowering the body appreciatively, friction is enhanced both by the angling and edging of the skis	Utilized primarily to decelerate, both on narrow and wide tracks
Skidding	Skidding is initiated by a distinct lowering of the body that results in unloading designed to maintain the skis parallel, with friction being enhanced by edging and angling of the skis	Utilized downhill for both turning and deceleration, on narrow as well as wide tracks
Tuck position	Tucking with neither pole nor leg action	Utilized downhill on relatively straight and wide tracks

The orienteering and cognitive aspects of ski-orienteering

A successful ski-orienteer must be able to navigate on a wide variety of different terrain and during different types of events (e.g., from sprint to long-distance, in either individual or mass-start races). Since, as mentioned above, each competitor receives the map only 15 s prior to start, they must navigate while skiing.

Thus, ski-orienteering performance is highly dependent on the skier's ability to interpret the topography, quality and width of the ski tracks, number of trail intersections and distances indicated on a two-dimensional map to determine the optimal route between controls. For instance, a shorter route may actually take more time if it involves more difficult terrain and/or orienteering. The varying quality of the ski tracks and the skier's rapid speed render these decisions particularly challenging. As in the case of orienteering on foot, the ability to continuously convert two-dimensional information from the map into the optimal three-dimensional route [17] requires good spatial cognition [18], e.g., reliable recognition of distinct features and symbols [19]. Mistakes, such as selecting the wrong intersection, can be more costly in terms of both energy and time than in the case of foot orienteering. For instance, skiing unnecessarily down a steep downhill on a narrow ski track can require a significant amount of time and energy to return uphill to the correct route.

During orienteering on foot, many skilled competitors simplify the information provided by the map [20–22] by focusing on the features most easily seen and, in particular, most useful for navigation. On less challenging sections of the course, they focus more heavily on the map [23] in order to plan for more challenging sections to come. Skilled orienteers also avoid unnecessary movement of the map during competition, maintaining the display of their present location directly in front of their eyes by adjusting the positioning of the map. As also mentioned above, unlike orienteers on foot, elite ski-orienteers rarely use their compass, but instead memorize the positions of crossings and trails (e.g., by counting and direction—first left, second right, third left, etc.). However, they may use the compass to orient the map towards the north, take a shortcut between trails and, of course, when confused/disoriented.

Ski-orienteers, like all elite athletes, involved in race competitions, face the challenge of managing distractions and physiological fatigue to maintain optimal cognitive performance throughout a race. Indeed, among their greatest challenges is maintaining focus on the orienteering (map) during the entire event. Clearly, this task is more difficult in races exceeding 90 min than events like a 12-min sprint. Mental fatigue, defined as "the inability to maintain concentration and process information for decision-making efficiently and effectively after a prolonged period of cognitively loaded activity" [24], significantly compounds this challenge, often reducing focus and prolonging reaction times. This is particularly critical in ski-orienteering, where athletes must make rapid decisions while skiing across unfamiliar terrain at high speed. While it is possible to relax momentarily on flat sections of a wider ski track that are easily navigated, it is crucial to regain concentration as soon as needed.

Training of a ski-orienteer

Because of the relative paucity of research on ski-orienteering, little is presently known concerning the training routines of athletes engaged in this sport. To improve our understanding of this matter, we conducted interviews with 16 international ski-orienteers (11 men and 5 women) from Norway, Sweden and Finland. The interview guide consisted of 12 closed-ended questions about the nature and volume of their training (for example, how many hours they trained during the last season; how many hours were performed at low, moderate and high intensity; how many of their training hours were conducted using different exercise modes, etc.). In addition, one open-ended question focusing on the participants' reflections about how sport science could potentially improve future ski orienteering performance was included in the interview guide. Standard ethical procedures, including approval by the Swedish Ethical Review Authority, voluntary participation with prior informed consent, and maintenance of confidentiality and anonymity, were strictly adhered to.

Physical training for ski-orienteering (Table 3)

As shown in Table 3, elite female ski-orienteers trained, on average, approximately 22% less the men. The reported volumes of training for both sexes are less extensive than those described previously for elite cross-country skiers and biathletes [11, 25] and more similar to those of elite orienteers [26]. Both the men and women performed most of their endurance training, either as skiing on snow or roller-skis or running with or without a map, at low intensity. In contrast, elite biathletes and cross-country skiers perform relatively more endurance training at low intensity [11, 25, 27]. The additional strength training, focusing specifically on the muscles of the upper body, performed by our ski-orienteers accounted for somewhat less of the total training time and resembled that documented for elite biathletes and cross-country skiers.

Table 3 Characteristics of the training performed by elite international male and female ski-orienteers

Variable	Unit	Training	
		Men (n = 11)	Women (n = 5)
Total volume of endurance and strength training	Hours/year (range)	$653 \pm 72^{\#}$ (range = 523–770)	536 ± 47 (range = 490–610)
Total volume of endurance training	Hours/year (range)	$603 \pm 63^{\#}$ (515–720)	494 ± 41 (450–560)
Training intensity distribution	Hours/year (average % of total) at		
	Low intensity	$497 \pm 79^{\#}$ (82%)	382 ± 59 (77%)
	Medium intensity	57 ± 23 (10%)	65 ± 25 (13%)
	High intensity	49 ± 30 (8%)	47 ± 15 (10%)
Type of endurance training	Hours/year (average % of total)		
	Skiing		
	On snow	177 ± 43 (30%)	166 ± 45 (34%)
	On roller-skis	150 ± 53 (25%)	94 ± 64 (19%)
	Combined	327 ± 90 (55%)	260 ± 92 (52%)
	Running (with and/or without a map)	223 ± 111 (36%)	147 ± 47 (30%)
	Other	52 ± 37 (12%)	88 ± 120 (12%)
Strength training	Hours/year	50 ± 26	42 ± 8
Overall distribution	Average % of all training combined		
	Low-intensity	76%	71%
	Medium-intensity	9%	12%
	High-intensity	7%	9%
	Strength	8%	8%

The values shown are means ± SD of self-reported values

$^{\#}p < 0.05$ for the values of the men versus the women, as calculated using the Mann–Whitney U-test

Statistically significant differences between the male and female ski-orienteers interviewed here were observed with respect to total training volume (i.e., endurance and strength combined), total hours of endurance training, and total hours of endurance training at low intensity. At the same time, as would be expected, there were differences between the individual athletes. These initial insights into the training of ski orienteers are based on interviews on a small number of athletes, including more men than women, and require confirmation with a more detailed follow-up study.

Training for the orienteering aspects of ski-orienteering

The opportunities for training actual ski-orienteering are often limited by lack of sufficient snow coverage, as well as the extensive time and effort required by coaches to prepare the ski tracks, set up courses, and position control points properly in the terrain. Consequently, every such opportunity is of great value, especially since there may be only 40–60 such opportunities, including 20–30 competitions, each winter.

This raises the question as to whether these athletes can improve their specific orienteering skills throughout the rest of the year in some other manner. Although orienteering in a suburban area using roller skis is one such possibility, this activity still demands extensive preparation. Alternatively, ski-orienteers can perform appropriate exercises on both skis and roller skis at varying speeds. One such exercise involves employing a map used previously to practice making choices concerning optimal routes, which reduces the need for preparation.

Indeed, in preparation for competitions, elite ski-orienteers, who are prohibited from visiting the area of competition in advance, attempt to obtain ski-orienteering and/or orienteering maps of the area utilized in previous competitions. Studying these maps can familiarize an athlete with the topography, the permanent network of (wide) cross-country ski-tracks, and the overall characteristics of the terrain.

Following races, ski-orienteers engage in extensive analysis and comparison of their choice of routes, focusing on mistakes and loss of time. This analysis is most effective when based on Global Positioning System (GPS) tracks (typically provided by the organizers after major competitions) in combination with the times required to navigate between sequential control points. Using this information, the athletes can focus on reducing or eliminating their weaknesses and improving their overall skills in order to avoid making similar mistakes in future competitions.

Future perspectives

The training and performance of male and female elite ski-orienteers can be optimized in a number of different ways, including more financial support allowing both year-round training and time for recovery. Ideally, the ski-orienteer should belong to an elite group at a center with high-quality training facilities, snow conditions and ski-tracks and the support of well-educated, experienced coaches. Monitoring of the individual skier's physiological and biomechanical characteristics and ski-orienteering technique, both in the laboratory and in the field, should be a key factor on which training is based.

Furthermore, as in the case of other sports, research focused on ski-orienteering should help improve the performance of these athletes. Among other aspects, such research should encompass: (1) physiological and biomechanical studies designed to improve strength and endurance, in particular of the upper body, as well as skiing technique, especially on narrow tracks; (2) analysis of performance and pacing during both training and competitions using a combination of GPS and motion tracker sensors to optimize the choice of route and performance under different conditions; (3) improvement of stress management, concentration, map reading, spatial orientation and decision-making; and (4) development of computer-based training designed to improve map memory and decision-making.

By integrating perspectives from the ski orienteers combined with our own knowledge and experience, we identified four specific research questions critical to advancing ski orienteering:

1. What training strategies are most effective and how can training be individualized?
2. Which biomechanical characteristics unique to ski-orienteering, i.e., differing from cross-country skiing, should the athletes focus on?
3. How can cognitive abilities such as map reading, spatial orientation, and route decision-making be improved on/off snow and could Virtual Reality (VR), Augmented Reality (AR), and/or Artificial Intelligence (AI) be useful in this context?
4. How can tracking of individual performance in real-time utilizing wearable technology be utilized to improve performance?

The International Orienteering Federation has been working actively to make this sport even more popular utilizing live TV broadcasts with GPS tracking of the athletes' positions, including cameras along the track and at the stadium (either involving drones or camera men who ski alongside the athletes on certain segments of the course) and skilled commentators. In addition, moving competitions closer to metropolitan areas and competing in smaller, more open areas with fewer obstacles could attract more spectators. More extensive use of chase start and sprint relay events, attractive competitive formats, would give spectators the possibility to follow exciting man-to-man duels. At the same time, measures of this sort will encourage more individuals to participate in ski-orienteering.

Finally, inclusion of ski-orienteering in major international multisport events is being promoted. As mentioned above, this sport is already an event in the Asian Winter Games, the Winter Universiade (World University Games), and the CISM World Military Winter Games and the International Orienteering Federation is actively pursuing its inclusion in the Winter Olympic Games. Inclusion of ski-orienteering in such prestigious events will not only broaden its media exposure and attract a more diverse audience, but also potentially attract additional financial support.

Acknowledgements We would like to thank all of the ski-orienteers who shared their experience and knowledge with us, without whom this analysis would not have been possible.

Author contributions JS and HCH designed the study. JS collected the data. JS and HCH analyzed the data. All authors contributed to writing the manuscript.

Funding Open access funding provided by Lulea University of Technology. The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability The data supporting the findings of this study are available from the corresponding author, Hans-Christer Holmberg, upon reasonable request.

Declarations

Conflict of interests The authors declare no competing interests.

Ethical approval and Informed consent Standard ethical procedures, including approval by the Swedish Ethical Review Authority, voluntary participation with prior informed consent, and maintenance of confidentiality and anonymity, were strictly adhered to.

References

1. International Orienteering Federation. Ski orienteering. https://orienteering.sport/skio/. Accessed on 2 Sep 2023
2. Wikipedia. World Ski Orienteering Championships. https://en.wikipedia.org/wiki/World_Ski_Orienteering_Championships. Accessed on 29 Mar 2024
3. Eventor. International Orienteering Federation Events. https://eventor.orienteering.org/Events/Show/6499. Accessed on 2 Sep 2023
4. Bliznevskiy AU, Porteous B, Kvåle HJ, Bliznevskaya VS, Nemec M, Ermakov SS, Kudryavtsev MD (2016) Comparative analysis of new sport types—potential candidates for inclusion in the winter Olympic games. J Phys Educ Sport 16(4):1334–1339
5. International University Sports Federation (2020) Ski orienteering upgraded to Winter World university games compulsory sport from 2027 inside the games. https://www.insidethegames.biz/articles/1101285/ski-orienteering-fisu-2027-university. Accessed on 29 Mar 2024
6. International Military Sports Council. CISM military World Winter games. https://www.milsport.one/events/cism-military-world-winter-games. Accessed on 2 Sep 2023
7. FasterSkier.com (2010) Ski-O Bids for spot in 2018 Olympics. https://fasterskier.com/2010/09/ski-o-bids-for-spot-in-2018-olympics/. Accessed on 29 Mar 2024
8. International Orienteering Federation. Competition rules-ski orienteering. https://orienteering.sport/skio/competition-rules/. Accessed on 2 Sep 2023
9. Pellegrini B, Stöggl T, Holmberg H-C (2018) Developments in the biomechanics and equipment of Olympic cross-country skiers. Front Physiol 24(9):976
10. Holmberg H-C (2015) The elite cross-country skier provides unique insights into human exercise physiology. Scand J Med Sci Sports 4:100–109
11. Sandbakk Ø, Holmberg H-C (2014) A reappraisal of success factors for Olympic cross-country skiing. Int J Sports Physiol Perform 9(1):117–121
12. SISU Idrottsböcker (2012) Svenska orienteringsförbundets utvecklingsplan för skidorientering, vol. 1, Stockholm, Sweden, pp 1–70
13. Sandbakk Ø, Hegge AM, Losnegard T, Skattebo Ø, Tønnessen E, Holmberg H-C (2016) The physiological capacity of the world's highest ranked female cross-country skiers. Med Sci Sports Exerc 48(6):1091–1100
14. Holmberg H-C, Rosdahl H, Svedenhag J (2007) Lung function, arterial saturation and oxygen uptake in elite cross-country skiers: influence of exercise mode. Scand J Med Sci Sports 17(4):437–444
15. Tønnessen E, Haugen TA, Hem E, Leirstein S, Seiler S (2015) Maximal aerobic capacity in the winter-Olympics endurance disciplines: Olympic-medal benchmarks for the time period 1990–2013. Int J Sports Physiol Perform 10(7):835–839
16. Pellegrini B, Sandbakk Ø, Stöggl T et al (2021) Methodological guidelines designed to improve the quality of research on cross-country skiing. J Sci Sport Exerc 3:207–223
17. Kolb H, Sobotka R, Werner R (1987) A model of performance-determining components in orienteering. Sci J Orienteer 3:71–81
18. Liu Y (2017) Research on the cognitive processing characteristics and skill training of map recognition in orienteering athletes. Northeast Normal University, Changchun
19. Rosofsky I (2005) Orienteering: the map sport. Faces People Places Cult 22:18
20. Eccles DW, Walsh SE, Ingledew DK (2002) A grounded theory of expert cognition in orienteering. J Sport Exerc Psychol 24:68–88
21. Eccles DW, Walsh SE, Ingledew DK (2002) The use of heuristics during route planning by expert and novice orienteers. J Sports Sci 20:327–337
22. Seiler R (1990) Decision making processing in orienteering: an action theoretical investigation. Int J Sport Psychol 21:36–45
23. Eccles DW, Walsh SE, Ingledew DK (2006) Visual attention in orienteers at different levels of experience. J Sports Sci 24:77–87
24. Lam HKN, Sproule J, Turner AP, Murgatroyd P, Gristwood G, Richards H, Phillips SM (2023) International orienteering experts' consensus on the definition, development, cause, impact and methods to reduce mental fatigue in orienteering: a Delphi study. J Sports Sci 40:2595–2607
25. Laaksonen MS, Jonsson M, Holmberg H-C (2018) The Olympic biathlon—recent advances and perspectives after Pyeongchang. Front Physiol 9:796
26. Tønnessen E, Svendsen IS, Rønnestad BR, Hisdal J, Haugen TA, Seiler S (2015) The annual training periodization of 8 world champions in orienteering. Int J Sports Physiol Perform 10(1):29–38
27. Sandbakk Ø, Holmberg HC (2017) Physiological capacity and training routines of elite cross-country skiers: approaching the upper limits of human endurance. Int J Sports Physiol Perform 12(8):1003–1011