Open Access Journal of Sports Medicine

Dovepress
open access to scientific and medical research

Open Access Full Text Article

ORIGINAL RESEARCH

The influence of sex, age, and race experience on pacing profiles during the 90 km Vasaloppet ski race

This article was published in the following Dove Press journal:
Open Access Journal of Sports Medicine
18 February 2016

Magnus Carlsson[1,2]
Hannes Assarsson[1]
Tomas Carlsson[1,2]

[1]School of Education, Health and Social Studies, Dalarna University, [2]Dala Sports Academy, Falun, Sweden

Abstract: The purpose of this study was to investigate pacing-profile differences during the 90 km Vasaloppet ski race related to the categories of sex, age, and race experience. Skiing times from eight sections (S1 to S8) were analyzed. For each of the three categories, 400 pairs of skiers were matched to have a finish time within 60 seconds, the same start group, and an assignment to the same group for the other two categories. Paired-samples Student's *t*-tests were used to investigate sectional pacing-profile differences between the subgroups. Results showed that males skied faster in S2 (P=0.0042), S3 (P=0.0049), S4 (P=0.010), and S1–S4 ($P<0.001$), whereas females skied faster in S6 ($P<0.001$), S7 ($P<0.001$), S8 (P=0.0088), and S5–S8 ($P<0.001$). For the age category, old subjects (40 to 59 years) skied faster than young subjects (19 to 39 years) in S3 (P=0.0029), and for the other sections, there were no differences. Experienced subjects (≥4 Vasaloppet ski race completions) skied faster in S1 ($P<0.001$) and S1–S4 (P=0.0054); inexperienced skiers (<4 Vasaloppet ski race completions) had a shorter mean skiing time in S5–S8 (P=0.0063). In conclusion, females had a more even pacing profile than that of males with the same finish time, start group, age, and race experience. No clear age-related pacing-profile difference was identified for the matched subgroups. Moreover, experienced skiers skied faster in the first half whereas inexperienced skiers had higher skiing speeds during the second half of the race.

Keywords: pacing strategy, cross-country skiing, endurance performance, sex difference.

Introduction

Recreational skiers have shown great interest in participating in long-distance (more than 50 km) cross-country ski races (eg, Vasaloppet, Marcialonga, and Birkebeiner-rennet). For example, more than 15,000 skiers participate in the 90 km Vasaloppet ski race (VSR) each year (http://www.vasaloppet.se). There is limited research about what type of qualities are needed to optimize performance in long-distance cross-country skiing races. Endurance-related physiological variables, such as maximal oxygen uptake and the work intensity at the lactate threshold, have been shown to be indicators of competitive distance (5 to 50 km) performance in cross-country skiing[1]; thus, it is likely that these physiological qualities are important for the performance in long-distance races. Another determinant of competitive endurance performance is how energetic resources are distributed to regulate power output.[2] In cross-country skiing, this means that a skier must efficiently exert propelling forces appropriate to the counteracting forces. This power-output regulation is related to the term pacing. Pacing has previously been defined as: "The goal directed distribution and management of effort across the duration of an exercise bout."[3] Hence, pacing in sports can be

Correspondence: Tomas Carlsson
School of Education, Health and Social Studies, Dalarna University, Högskolegatan 2, 79188 Falun, Sweden
Tel +46 23 778 402
Fax +46 23 794 324
Email tca@du.se

submit your manuscript | www.dovepress.com
Dovepress
http://dx.doi.org/10.2147/OAJSM.S101995

regarded as a strategy to distribute the power output during the exercise, which is influenced by both physiological and psychological factors.[3]

The influence of pacing in cross-country skiing has previously been investigated based on skiing speed for a 1.4 km sprint[4] and 5.6–50 km distance[5–9] performances; together, these studies indicate that cross-country skiers tend to adopt a positive pacing profile (ie, race speed gradually decreasing throughout the race). This pacing strategy has been questioned by a numerical simulation of sprint skiing that claims that an even pacing profile, characterized by minor variations in skiing speed, is optimal for performance.[10] However, there is presently no detailed information available about how a skier should regulate his/her power output to optimize performance in long-distance races.

An athlete's pacing profile in a self-paced competition is influenced by a predetermined pacing strategy and an alteration in homeostatic status during the race; hence, the power output is regulated by the brain, at various subconscious to conscious levels, according to the afferent feedback from numerous physiological systems to reduce the risk of critical homeostatic disturbances.[11] It has been suggested that athletes, during the event, continuously compare their rate of perceived exertion with the expected rate of perceived exertion, and if these diverge, the athletes increase or decrease the pace.[12] Different pacing profiles have been proposed to optimize performance depending on the exercise duration; for marathon running with an approximate duration of 2.5 hours, a more even pacing profile has been associated with better performance.[13–15] Information about the optimal pacing profile for performances that last more than 5 hours is limited; however, it has been suggested that an even pacing profile was preferable for a 100 km ultramarathon running performance where the mean race time was ~8 hours.[16]

A recent investigation regarding the pacing profiles of marathoners demonstrated that both males and females tried to maintain an even pacing profile; however, independent of the performance level, all groups displayed a positive pacing profile (ie, the race speed gradually decreased throughout the race).[17] However, it appears that females are more likely than males to adopt a more even pacing profile during marathon running.[18,19] It has been proposed that these sex differences originate from both physiological and psychological differences between males and females.[19]

Differences in pacing profiles have also been shown for athletes with different ages, where older marathon runners were shown to have a more even pacing profile compared to that of their younger counterparts.[18] Another proposed influencing factor on athletes' pacing is previous race experience. A previous study showed that experienced marathon runners were able to keep their pace better than less experienced marathon runners.[19] It has been suggested that inexperienced athletes tend to overestimate their individual capability, which contributes to a more pronounced positive pacing profile; this requires a downregulation of power output as a consequence of a premature sensation of fatigue.[3] Hence, previous race experience appears to be an important factor for adopting an accurate pacing strategy for the specific exercise task.

The purpose of the current study was to investigate pacing-profile differences during the 90 km VSR related to the categories of sex, age, and race experience. We hypothesized that there was a larger proportion of females, old, and experience skiers who skied slower in the sections during first half and faster in the sections during the second half in the 90 km VSR compared to males, young, and inexperienced skiers, respectively.

Methods

Study design

To investigate pacing-profile differences for the categories of sex, age, and race experience for a long-distance cross-country skiing race, skiing times from the 90 km VSR were analyzed. To minimize the effect of weather and waxing on performance, results from the VSR year 2012 (http://results.vasaloppet.se) were chosen because of the stable track and weather conditions throughout the race. For each category, the subjects were matched based on finish time, start group, and the other two categories. The Institutional Review Board granted approval for this study, and the requirement for written informed consent was waived because all data were publicly available.

Race characteristics

The 90 km VSR is a mass-start competition and the skiers are, based on their results from cross-country skiing races approved by Vasaloppet organization, assigned to eleven different start groups (start groups 0 to 10). The race is performed using the classical technique. The weather conditions throughout the race were stable with an air temperature below zero (–9°C at the start, –1°C at midday, and –3°C during the afternoon). The 90 km course had 1,380 m of total climbing, an altitude difference of 360 m, and a maximum continuous climbing section of 180 m. In addition to the finish time, split times were recorded at seven official intermediate-time stations, and the course was divided into eight sections (S1 to S8) (Figure 1). The sections had the following distances: S1, 11.0

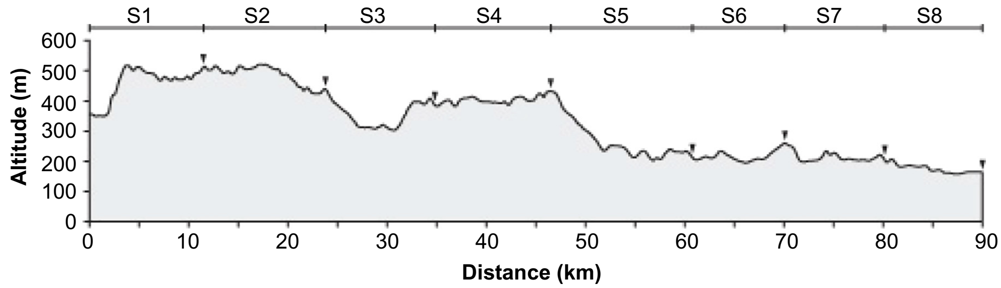

Figure 1 Course profile of the 90 km Vasaloppet ski race and placement of the intermediate-time stations (▼), which divide the course into eight sections (S1 to S8).

km; S2, 13.0 km; S3, 10.9 km; S4, 13.1 km; S5, 14.0 km; S6, 9.0 km; S7, 10.0 km; and S8, 9.0 km. A total of 13,765 skiers (12,289 males and 1,476 females) finished the race, with the fastest skier completing the course in 3:38:41 hh:mm:ss.

Matching procedure

All skiers who were aged from 19 to 59 years, started in start groups 1 to 9, and finished the race were considered potential subjects for the study. The skiers were assigned to a start group based on seeding results from cross-country skiing races approved by Vasaloppet organization to ensure that the skiers were assigned to a start group that best suited their skiing ability. Unseeded first-time participants were assigned to the start group 10. Therefore, skiers from this start group were excluded because they entered the race unseeded, and we assumed that a high percentage had the aim to just finish the race without any ambition to achieve the best possible finish time. We postulated that skiers from the start group 0 (elite group) had the ambition to win the race or attain the best possible finishing position, and their pace were therefore greatly influenced by the pacing strategies of their competitors. Participants aged 60 years or older were also excluded to obtain two age-group intervals of 20 years for the matching procedure. After the inclusion/exclusion process based on the preset conditions mentioned earlier, the sample of potential subjects consisted of 9,691 recreational skiers.

The skiers were assigned to one of two subgroups for each category. Sex was divided into males and females, whereas the subgroups for age were divided into young (19 to 39 years) and old (40 to 59 years). For the race-experience category, the skiers were divided into inexperienced skiers comprising subjects who had completed the 90 km course less than four times and experienced skiers, that is, skiers with race experience from four or more races on the 90 km course. The differentiation between inexperienced and experienced skiers was based on the results showing that approximately four races in a 56 km ultramarathon were required to optimize performance,[20] and that athletes with less than 4 years of experience had a larger decrease in their pace during the course of a marathon compared with the decrease of the experienced athletes.[19] To investigate a specific category's influence on the pacing profile during the VSR, the subjects were matched based on finish time, start group, and the other two categories to minimize their influence on the results of the statistical analysis.

For each category, a random selection of subjects from the subgroup with the lowest number of potential subjects was performed (sex, 8,788 males and 903 females; age, 5,535 old and 4,156 young; race experience, 6,506 inexperienced and 3,185 experienced). Sequentially, each selected subject was then matched with the subject from the category's other subgroup who had the most similar finish time (within 60 seconds), who also started from the same start group, and was part of the same subgroup for the other two categories. This means that the matches had similar conditions throughout the race because of the stable track and weather conditions and the opportunities to draft behind competitors. If no match was identified, the subject was excluded. The matching procedure was repeated until 400 matches were found for each category. The number of subjects for whom no match was identified was 77, 101, and 37 for the sex, age, and race experience categories, respectively. The mean difference for the finish times between the subgroups for each category was –1±18 seconds (mean ± standard deviation) for sex, 0±20 seconds for age, and 1±14 seconds for race experience.

Subjects

The compositions of the matched groups for each category are presented in Table 1; these groups were used for the subsequent investigation of pacing-profile differences.

Statistical analyses

To determine whether the two groups of matched skiers in a category had a different pacing profile for each specific

Table 1 Characteristics of the matched subgroups for each category

Matching criteria	Sex		Age		Race experience	
	Male	Female	Old	Young	Exp	Inexp
Age	39±10	38±10	47±5	33±5	45±8	43±8
Race experience	3±5	3±3	5±6	4±4	9±5	1±1
Start group	7±2	7±2	5±2	5±2	5±2	5±2
Finish time	7:15±1:06	7:15±1:06	6:24±1:13	6:24±1:13	6:14±1:10	6:14±1:10
Sex	♂400 ♀0	♂0 ♀400	♂382 ♀18	♂382 ♀18	♂386 ♀14	♂386 ♀14

Note: All values are presented as the mean ± standard deviation for each subgroup; Age, the age of the subjects (years); Race experience, the subject's previous race experience on the 90 km course (number of completed races); Start group, the start group of the subjects (number); Finish time, the finish time of the subjects (hours:minutes); Sex, the composition of males (♂) and females (♀) in each subgroup (number); Old, subjects aged between 40 and 59 years; Young, subjects aged between 19 and 39 years; Experienced (Exp) subjects who had completed the 90 km course more than three times; Inexperienced (Inexp) subjects who had completed the 90 km course zero to three times.

section (S1–S8), paired-samples Student's *t*-tests were conducted. A Bonferroni adjustment was applied to correct for the number of statistical tests performed, and all the presented *P*-values for the pacing-profile differences are adjusted. The described procedure was repeated for all categories and sections of the 90 km course. All tests were performed at an alpha of 0.05. The statistical analyses were conducted using the IBM SPSS Statistics software, version 20 (IBM Corporation, Armonk, NY, USA).

Results

Section-time differences between subgroups and pacing-profile differences for each section in the VSR are presented in Table 2. Males skied faster in S2 (P=0.0042), S3 (P=0.0049), S4 (P=0.010), and for the first half of the race (S1–S4) ($P<0.001$), whereas females skied faster in S6 ($P<0.001$), S7 ($P<0.001$), S8 (P=0.0088), and for the second half of the race (S5–S8) ($P<0.001$). For the age category, old skiers had a faster pace than their matches in S3 (P=0.0029), and for the other seven sections, there were no differences. Experienced skiers skied faster than their less experienced counterparts in S1 ($P<0.001$) whereas no pacing-profile difference was found for any of the subsequent sections. However, in S1–S4, the experienced skiers had a faster pace (P=0.0054) whereas in S5–S8 the inexperienced skiers had a shorter mean skiing time (P=0.0063).

The accumulated mean time difference between the subgroups for each category and section is displayed in Figure 2. For all subgroups combined, the race speeds were as follows: total race distance, 14.1±2.7 km·h^{-1}; S1, 11.1±3.3 km·h^{-1}; S2, 16.1±2.6 km·h^{-1}; S3, 15.8±2.9 km·h^{-1}; S4, 14.9±2.7 km·h^{-1}; S5, 14.8±2.9 km·h^{-1}; S6, 12.8±2.4 km·h^{-1}; S7, 13.5±2.3 km·h^{-1}; and S8, 14.6±2.3 km·h^{-1}.

Discussion

The current study provide novel insights into pacing-profile differences in long-distance cross-country skiing and the results show that there are sex and race-experience

Table 2 Section-time differences between subgroups and pacing-profile differences for each section in the 90 km Vasaloppet ski race

Course section	Sex		Age		Race experience	
	Male–Female	Student's t-value	Young–Old	Student's t-value	Inexp–Exp	Student's t-value
S1	35±392	1.78	–16±303	–1.08	93±340	5.47***
S2	–84±472	–3.56**	12±143	1.72	0±132	0.00
S3	–77±441	–3.51**	21±116	3.65**	–13±112	–2.27
S4	–31±187	–3.30*	13±133	1.89	–17±135	–2.57
S5	19±224	1.69	–15±175	–1.72	–19±173	–2.16
S6	50±171	5.91***	–10±145	–1.37	–14±131	–2.12
S7	62±145	8.61***	–10±134	–1.42	–12±171	–1.40
S8	26±157	3.35**	5±131	0.79	–18±134	–2.63
S1–S4	–157±418	–7.54***	30±368	1.62	63±361	3.49**
S5–S8	158±417	7.57***	–29±368	–1.59	–62±361	–3.45**

Notes: Section-time differences (mean ± standard deviation) in seconds between subgroups (male–female; young–old; inexperienced [inexp]–experienced [exp]) in each category (sex; age; race experience). Results of paired-samples Student's *t*-tests (Student's *t*-value) were used to investigate sectional pacing-profile differences between the subgroups and alpha levels for significant differences in section times for S1 to S8, the first half of the race (S1–S4) and the second half of the race (S5–S8) are reported as *for $P<0.05$; **for $P<0.01$; and ***for $P<0.001$. All the presented significance levels for the pacing-profile differences are Bonferroni adjusted.

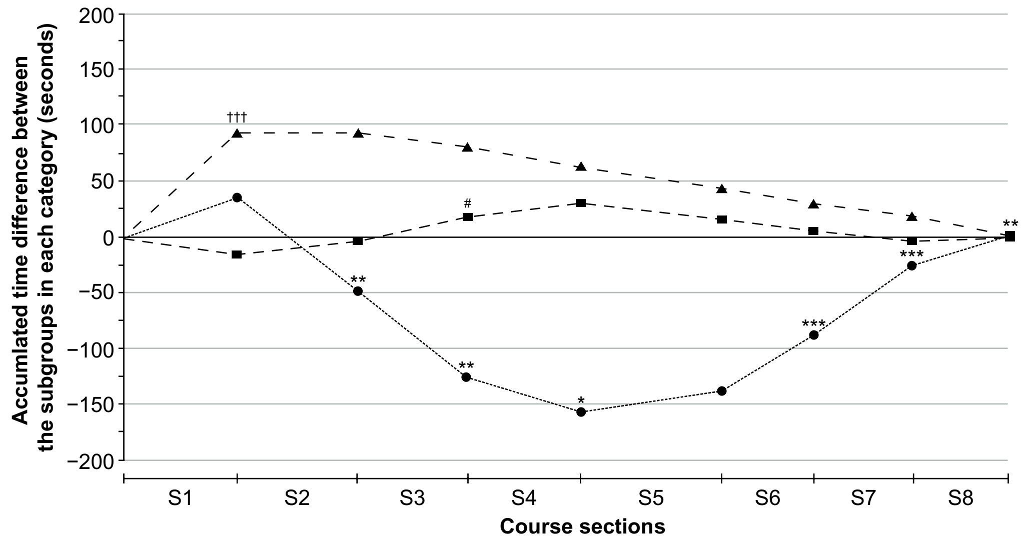

Figure 2 The accumulated mean time difference in the 90 km VSR between the subgroups for each category (sex, ●; age, ■; and race experience, ▲) and section (S1 to S8) calculated as "male–female," "young–old," and "inexperienced–experienced."

Notes: For example, a positive accumulated mean time difference indicates that subcategories female, old, and experienced skiers are ahead of their matched counterparts. Significant differences in section times for S1 to S8 are reported as: *for $P<0.05$, **for $P<0.01$, and ***for $P<0.001$ for the sex category; #for $P<0.01$ for the age category; and †††for $P<0.001$ for the race-experience category.

Abbreviation: VSR, Vasaloppet ski race.

differences in the pacing profiles in the 90 km VSR. In general, females skied slower during the first half and faster during the second half of the race compared with the males with the same performance level, start group, age, and race experience. Except for one section (S3), where the older skiers were faster, there was no significant age-related difference in pacing profile. Experienced skiers had a faster pace during the first section; however, no pacing-profile difference was found for any of remaining seven sections. When the 90 km VSR was split into two halves, experienced skiers skied faster during the first half whereas the inexperienced skiers were faster during the second half.

For the performance in ultramarathon running with a mean race duration of 8 hours, it was shown that better performers were able to maintain their initial speed longer and had lower variations in race speed.[16] Similarly, the mean race time for the subjects in the current study was ~6.5 hours, and an even pace profile could therefore be expected to optimize skiing performance; however, skiing speeds vary largely due to fluctuations in the counteracting forces (eg, a net increase in potential energy on uphill slopes, air resistance, friction between skis and snow), in particular, as a result of changes in terrain. Hence, one cannot expect an equal mean skiing speed for all sections even if the propulsive forces/power output is evenly distributed throughout the 90 km VSR. Thus, using the commonly used pacing definitions (ie, positive, even, and negative) can be problematic when analyzing the pacing profile of an individual skier. However, because the matched pairs have a similar finish time (within 60 seconds), the current study permits comparisons of the pacing profiles of the category's subgroups.

Sex-related pacing-profile differences

When the skiing times for each section were compared for the matched pairs in the sex category, females had a slower pace during the first half but skied faster than males during the second half. Comparison of the mean section speeds showed that females had a more even (or less positive) pacing profile compared with that of males. This result is consistent with the results from investigations on sex differences in nonelite runners during a marathon.[18,19] The females' ability to maintain higher section speeds during the second half of the race is also supported by results from a previous study showing that for males and females with an equal level of performance in marathon running, the females were significantly faster in a 90 km ultramarathon.[21] There could be several potential physiologically- and psychologically-based factors that contribute to sex-related pacing-profile differences in endurance events.

It has been shown that females have a greater proportional area of type I fibers.[22,23] Compared with type II fibers, type I muscle fibers are more fatigue-resistant,[24] and the females greater proportional area of type I fibers could, therefore, be advantageous for endurance performances with long duration. Moreover, it has been shown that females have higher rates of fat oxidation and a later shift to the use of carbohydrates as the dominant fuel.[25,26] This sex difference in substrate utilization has been established for endurance exercise at different intensities,[26,27] and exists independently of training status.[26] At the same relative work intensity, females utilize a lower proportion of carbohydrates compared to males and are therefore at lower risk for fatigue-related muscle-glycogen depletion.[28]

These physiological differences between females and males could contribute to the males more positive pacing profile compared to the females. Males have in general a larger area of type II muscle fibers,[22,23] and it has been shown that male skiers also have a greater muscle mass in both upper and lower body[29]; these physiological characteristics contribute to males greater ability to produce power.[30] A high power production is related to both a high skiing speed and high-energy expenditure.[31] Males higher skiing speeds during the first half of the VSR could therefore increase the risk for fatigue-related muscle-glycogen depletion,[28] and the availability of carbohydrates has been shown to be critical for performances with a duration of more than 90 minutes.[32,33]

Consistent with the concept of teleoanticipation,[34] the brain response to the sensory feedback, concerning muscle-glycogen depletion and increased concentration of fatigue-related metabolites, is a downregulation of the power output to optimize performance. The purpose of this power-output regulation is to restrict the exercise-induced peripheral muscle fatigue and/or sensory feedback associated with the exercise in relation to a certain individual critical threshold of muscle afferent feedback.[35,36] Athletes with a more pronounced positive pacing strategy must reduce their race speed toward the end of a race to reduce the risk of critical homeostatic disturbances.[12,37] Together, these physiological factors could help explain why males, compared to females, have a more pronounced positive pacing profile during the VSR.

In addition to these physiological factors, the established sex-related pacing-profile difference could also be influenced by psychological factors, such as level of competitiveness. For distance runners, males were reported to have a greater competitiveness and be more win orientated compared to females.[38] In marathon running, males are more likely to reduce their speed toward the end of the race.[18,19] This sex difference could be a reflection of males greater risk taking, which is a component of competitiveness.[38] As a result of males being more competitive, they have a 1.8 higher prevalence of "hitting the wall" in marathons.[39] This established sex difference in competitiveness and its influence on pacing could, together with the previously mentioned physiological factors, be a contributing factor to why males ski faster than females in the first half of the VSR.

Generally, for any given level of talent and training, there is a 10%–12% sex-related difference in endurance performance.[40,41] This difference is mainly attributed to males' higher maximal oxygen uptake and lower percentage of body fat.[42,43] In view of the expected endurance-performance difference between males and females, the finish-time matching in the current study could potentially indicate that the females, in a matched pair, is more talented and/or better trained than the male. A better training status could, in this respect, result in a less slowing in pace for females during the second half of the VSR. However, it has been shown that there is a sex-related pacing-profile difference in marathon despite a 12% adjustment to females' performances.[19] The demonstrated pacing-profile difference related to sex, in the current study, is most likely influenced by both physiological and psychological differences between male and female participants in VSR.

Age-related pacing-profile differences

Previously, an age-related difference in pacing profiles was reported in marathon running where older runners adopted a more even pace than that of their younger competitors[18]; however, they did not control for the influence of running experience on the results. Hence, the effect of age on pacing could be somewhat overestimated. In the current study, there was no significant age-related difference in the pacing profile except during S3, where the younger skiers were faster. The effect of age in the aforementioned study of marathoners was observed when the subgroup $\leq$34 years was compared with older age groups (35–44 and 45+).[18] Hence, another reason for the lack of age-related pacing-profile differences in the current study could be that the mean age in the young subgroup (33 years) was too old to detect the potential age effect.

Race experience-related pacing-profile differences

Race experience has previously been related to marathon performance; experienced runners had a more even pace than that of inexperienced runners who displayed a greater decrease in pace at the end of the race.[19] The total number of completed marathons partly explained the variation in pacing, independent of the effects of age, finishing time, and sex. In the current study, we controlled for the effect of these factors by matching the subjects, and the results revealed that experienced skiers skied faster during S1. No significant pacing-profile difference was found for any of the subsequent sections, although, the accumulated time difference between experienced and inexperienced skiers is gradually reduced from S3 to S8 (Figure 2). When the skiing times for the two halves of the race were analyzed, experienced skiers had a higher pace during the first half whereas the inexperienced skiers were faster during the second half of the VSR. The overall pacing-profile difference between experienced and inexperienced skiers is opposite to the pacing pattern that was detected for marathoners.[19] Plausible explanations for the experienced skiers' higher section speed during S1 could be the starting procedure and characteristics of the initial part of S1.

In the VSR, each start group has a designated place at the start area, and the groups with lower seeding are positioned in front of the groups with higher seeding. At the start, there are 52 tracks, and after 2 km, these tracks are merged into eight tracks at the beginning of the first uphill segment. Because the performance during S1 is most likely influenced by the position when entering the uphill segment, it appears that experienced skiers obtained a better position at the track merging. This could be a result of an earlier entry into the start area, which makes it possible for the experienced skiers to place their skis as close as possible to the front row of the specific start group, and/or adoption of a faster start pace than that of the inexperienced skiers. Moreover, a plausible explanation to the inexperienced skiers' higher skiing speeds during the second half of the race could be a reflection of a somewhat better physiological capability of the inexperienced skiers compared to their matches. This assumption is supported by previous studies where faster ultramarathon runners had a more even pacing profile.[16]

Strengths and limitations

There are several potential physiological and psychological factors that could influence the skiers' pacing throughout the race, which in an optimal situation should be controlled for. For example, in the current study, no individual data were available concerning the participants' physiological capability, skiing-specific technical skills, carbohydrate ingestion during the race, incidents, and waxing of the skis. However, because of the large sample size, it could be assumed the effect of section times from individuals with extreme values for any of the possible influencing factors would not have a substantial effect on the results presented here. When the influence of previous race experience on pacing was investigated, the participants' previous race experience in the VSR was used as the variable of experience. Previous experience of the specific race is an important factor for optimal pacing; however, it would also have been valuable to have information about the participants' race experience in other long-distance cross-country skiing races. In future research investigating pacing-profile differences in long-distance skiing, it is recommended to gather individual data about factors that potentially could influence race performance. Furthermore, in the current study, the analyses of the influence of race experience and age on pacing profiles are based on an unequal distribution of male and female subjects in the subgroups related to each category. Hence, further research should investigate if sex influences the pacing profiles in long-distance cross-country skiing for skiers with different race experience and age. In a future perspective, when investigating sex-related pacing-profile differences in long-distance cross-country skiing, an inclusion of a 10%–12% performance-difference adjustment between males and females would be appropriate; however, this adjustment would entail that males and females will have different prerequisites during the race because of, for example, different start groups, track preparations, and weather conditions, which in turn would influence the pacing analyses.

Conclusion and practical applications

The current study demonstrates that females have a more even (or less positive) pacing profile during the 90 km VSR compared with the profile of males who have the same finish time, start group, age, and race experience. In general, males skied faster during the first half of the race, whereas females had a higher skiing speed during the second half. Based on these conclusions, males would probably benefit from a slower start pace during the first half of the VSR. No clear age-related pacing-profile difference was identified for the matched subgroups of old and young skiers. Moreover, experienced skiers skied faster in the first section than their matches; conversely, the accumulated time difference between experienced and inexperienced skiers is gradually reduced from S3 to S8, which is supported by the inexperienced skiers' higher skiing speed during the second half of the race. In order to optimize performance in long-distance cross-country skiing, it could be beneficial for the skiers to pay attention to pacing-related factors during training and competition to increase their knowledge about individual capabilities under different circumstances.

Disclosure

The authors report no conflicts of interest in this work.

References

1. Carlsson M, Carlsson T, Hammarström D, Tiivel T, Malm C, Tonkonogi M. Validation of physiological tests in relation to competitive performances in elite male distance cross-country skiing. *J Strength Cond Res*. 2012;26(6):1496–1504.
2. de Koning JJ, Bobbert MF, Foster C. Determination of optimal pacing strategy in track cycling with an energy flow model. *J Sci Med Sport*. 1999;2(3):266–277.
3. Edwards A, Polman R. *Pacing in Sport and Exercise*: *A Psychophysiological Perspective*. New York: Nova Science Publishers; 2012.
4. Andersson E, Supej M, Sandbakk Ø, Sperlich B, Stöggl T, Holmberg HC. Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur J Appl Physiol*. 2010;110(3):585–595.
5. Bilodeau B, Rundell KW, Roy B, Boulay MR. Kinematics of cross-country ski racing. *Med Sci Sports Exerc*. 1996;28(1):128–138.
6. Bolger CM, Kocbach J, Hegge AM, Sandbakk O. Speed and heart rate profiles in skating and classical cross-country skiing competitions. *Int J Sports Physiol Perform*. 2015;10:873–880.
7. Larsson P, Henriksson-Larsen K. Combined metabolic gas analyser and dGPS analysis of performance in cross-country skiing. *J Sports Sci*. 2005;23(8):861–870.
8. Formenti D, Rossi A, Calogiuri G, Thomassen TO, Scurati R, Weydahl A. Exercise intensity and pacing strategy of cross-country skiers during a 10 km skating simulated race. *Res Sports Med*. 2015;23(2):126–139.
9. Carlsson T, Carlsson M, Hammarström D, Rønnestad BR, Malm CB, Tonkonogi M. Optimal VO2max-to-mass ratio for predicting 15 km performance among elite male cross-country skiers. *Open Access J Sports Med*. 2015;6:353–360.
10. Sundström D, Carlsson P, Ståhl F, Tinnsten M. Numerical optimization of pacing strategy in cross-country skiing. *Struct Multidiscipl Optim*. 2013;47(6):943–950.
11. Edwards AM, Polman RCJ. Pacing and awareness: brain regulation of physical activity. *Sports Med*. 2013;43(11):1057–1064.
12. de Koning JJ, Foster C, Bakkum A, et al. Regulation of pacing strategy during athletic competition. *PLoS One*. 2011;6(1)e15863.
13. Ely MR, Martin DE, Cheuvront SN, Montain SJ. Effect of ambient temperature on marathon pacing is dependent on runner ability. *Med Sci Sports Exerc*. 2008;40(9):1675–1680.
14. Erdmann WS, Lipinska P. Kinematics of marathon running tactics. *Hum Mov Sci*. 2013;32(6):1379–1392.
15. Maughan RJ, Leiper JB, Thompson J. Rectal temperature after marathon running. *Br J Sports Med*. 1985;19(4):192–195.
16. Lambert MI, Dugas JP, Kirkman MC, Mokone GG, Waldeck MR. Changes in running speeds in a 100 km ultra-marathon race. *J Sports Sci Med*. 2004;3(3):167–173.
17. Santos-Lozano A, Collado PS, Foster C, Lucia A, Garatachea N. Influence of sex and level on marathon pacing strategy. Insights from the New York City race. *Int J Sports Med*. 2014;35(11):933–938.
18. March DS, Vanderburgh PM, Titlebaum PJ, Hoops ML. Age, sex, and finish time as determinants of pacing in the marathon. *J Strength Cond Res*. 2011;25(2):386–391.
19. Deaner RO, Carter RE, Joyner MJ, Hunter SK. Men are more likely than women to slow in the marathon. *Med Sci Sports Exerc*. 2015;47(3):607–616.
20. Rae DE, Bosch AN, Collins M, Lambert MI. The interaction of aging and 10 years of racing on ultraendurance running performance. *J Aging Phys Act*. 2005;13(2):210–222.
21. Speechly DP, Taylor SR, Rogers GG. Differences in ultra-endurance exercise in performance-matched male and female runners. *Med Sci Sports Exerc*. 1996;28(3):359–365.
22. Esbjörnsson-Liljedahl M, Sundberg CJ, Norman B, Jansson E. Metabolic response in type I and type II muscle fibers during a 30-s cycle sprint in men and women. *J Appl Physiol*. 1999;87(4):1326–1332.
23. Carter SL, Rennie CD, Hamilton SJ, Tarnopolsky. Changes in skeletal muscle in males and females following endurance training. *Can J Physiol Pharmacol*. 2001;79(5):386–392.
24. Hunter SK. Sex differences in human fatigability: mechanisms and insight to physiological responses. *Acta Physiol*. 2014;210(4):768–789.
25. Venables MC, Achten J, Jeukendrup AE. Determinants of fat oxidation during exercise in healthy men and women: a cross-sectional study. *J Appl Physiol*. 2005;98(1):160–167.
26. Carter SL, Rennie C, Tarnopolsky MA. Substrate utilization during endurance exercise in men and women after endurance training. *Am J Physiol Endocrinol Metab*. 2001;280(6):E898–E907.
27. Horton TJ, Pagliassotti MJ, Hobbs K, Hill JO. Fuel metabolism in men and women during and after long-duration exercise. *J Appl Physiol*. 1998;85(5):1823–1832.
28. Hermansen L, Hultman E, Saltin B. Muscle glycogen during prolonged severe exercise. *Acta Physiol Scand*. 1967;71(2):129–139.
29. Carlsson M, Carlsson T, Hammarström D, Malm C, Tonkonogi M. Prediction of race performance of elite cross-country skiers by lean mass. *Int J Sports Physiol Perform*. 2014;9(6):1040–1045.
30. Sandbakk Ø, Ettema G, Holmberg HC. Gender differences in endurance performance by elite cross-country skiers are influenced by the contribution from poling. *Scand J Med Sci Sports*. 2014;24(1):28–33.
31. Bergh U. The influence of body mass in cross-country skiing. *Med Sci Sports Exerc*. 1987;19(4):324–331.
32. Coyle EF, Hagberg JM, Hurley BF, Martin WH, Ehsani AA, Holloszy JO. Carbohydrate feeding during prolonged strenuous exercise can delay fatigue. *J Appl Physiol Respir Environ Exerc Physiol*. 1983;55(1 Pt 1):230–235.
33. Karlsson J, Saltin B. Diet, muscle glycogen, and endurance performance. *J Appl Physiol*. 1971;31(2):203–206.
34. Ulmer HV. Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. *Experientia*. 1996;52(5):416–420.
35. Amann M. Central and peripheral fatigue: interaction during cycling exercise in humans. *Med Sci Sports Exerc*. 2011;43(11):2039–2045.
36. Amann M, Eldridge MW, Lovering AT, Stickland MK, Pegelow DF, Dempsey JA. Arterial oxygenation influences central motor output and exercise performance via effects on peripheral locomotor muscle fatigue in humans. *J Physiol*. 2006;575(3):937–952.
37. Gibson AS, Noakes TD. Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *Br J Sports Med*. 2004;38(6):797–806.
38. Deaner RO, Lowen A, Rogers W, Saksa E. Does the sex difference in competitiveness decrease in selective sub-populations? A test with intercollegiate distance runners. *Peerj*. 2015;3:e884.
39. Buman MP, Brewer BW, Cornelius AE, Van Raalte JL, Petitpas AJ. Hitting the wall in the marathon: phenomenological characteristics and associations with expectancy, gender, and running history. *Psychol Sport Exerc*. 2008;9(2):177–190.
40. Sparling PB, O'Donnell EM, Snow TK. The gender difference in distance running performance has plateaued: an analysis of world rankings from 1980 to 1996. *Med Sci Sports Exerc*. 1998;30(12):1725–1729.
41. Thibault V, Guillaume M, Berthelot G, et al. Women and men in sport performance: the gender gap has not evolved since 1983. *J Sports Sci Med*. 2010;9(2):214–223.
42. Calbet JAL, Joyner MJ. Disparity in regional and systemic circulatory capacities: do they affect the regulation of the circulation? *Acta Physiol (Oxf)*. 2010;199(4):393–406.
43. Joyner MJ. Physiological limiting factors and distance running: influence of gender and age on record performances. *Exerc Sport Sci Rev*. 1993;21:103–133.