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INVITED COMMENTARY

A Reappraisal of Success Factors for Olympic Cross-Country Skiing

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Cross-country (XC) skiing has been an Olympic event since the first Winter Games in Chamonix, France, in 1924. Due to more effective training and tremendous improvements in equipment and track preparation, the speed of Olympic XC-ski races has increased more than that of any other Olympic endurance sport. Moreover, pursuit, mass-start, and sprint races have been introduced. Indeed, 10 of the 12 current Olympic competitions in XC skiing involve mass starts, in which tactics play a major role and the outcome is often decided in the final sprint. Accordingly, reappraisal of the success factors for performance in this context is required. The very high aerobic capacity (VO_{2max}) of many of today's world-class skiers is similar that of their predecessors. At the same time, the new events provide more opportunities to profit from anaerobic capacity, upper-body power, high-speed techniques, and "tactical flexibility." The wide range of speeds and slopes involved in XC skiing requires skiers to continuously alternate between and adapt different subtechniques during a race. This technical complexity places a premium on efficiency. The relative amounts of endurance training performed at different levels of intensity have remained essentially constant during the past 4 decades. However, in preparation for the Sochi Olympics in 2014, XC skiers are performing more endurance training on roller skis on competition-specific terrain, placing greater focus on upper-body power and more systematically performing strength training and skiing at high speeds than previously.

***Keywords**:* aerobic capacity, anaerobic capacity, efficiency, maximal oxygen uptake, speed, strength, tactics, technique

Cross-country skiing, regarded as one of the most demanding endurance sports, has been an Olympic event since the first Winter Games in Chamonix, France, in 1924. More effective training and tremendous improvements in equipment and track preparation have led to greater increases in speeds in this event than in any other Olympic endurance sport (Figure 1). Beginning in the middle of the 1980s, a number of major changes have been introduced into cross-country skiing, starting with introduction of the skating technique and followed by various types of pursuit, mass-start, and sprint races. In connection with the Sochi Olympics in Russia 2014, both female and male cross-country skiers will face the following challenges:

- 10- and 15-km individual time trials, respectively, employing the classical technique
- 15- and 30-km pursuit races, respectively, during which the skiers use the classical technique over the first half of the distance and the skating technique for the second half
- 30- and 50-km mass-start races respectively, with the skating technique
- 1.3- and 1.8-km sprint skating races, respectively, including a qualifying race and 3 subsequent knockout heats with 6 skiers in each
- Relay races involving four 5- and 10-km sections, respectively, during the first 2 of which the classical and the last 2 the skating technique is used
- A qualifying sprint relay and final heat utilizing the classical technique, with three 1.3- and 1.8-km sections, respectively, for each of the 2 skiers on each team

Eight of the 12 cross-country skiing events to be held in Sochi either did not exist or have been significantly altered in format since the Lillehammer games in 1994. These rather extensive changes motivate a reappraisal of the success factors for performance of Olympic cross-country skiers and the related consequences for training and specialization in sprint and distance competitions.

The Demands of Olympic Cross-Country Skiing

Although cross-country-skiing races can last from 12 minutes (4 races of 3 min in sprint skiing) to over 2 hours (in a 50-km race), 10 of the 12 Olympic competitions

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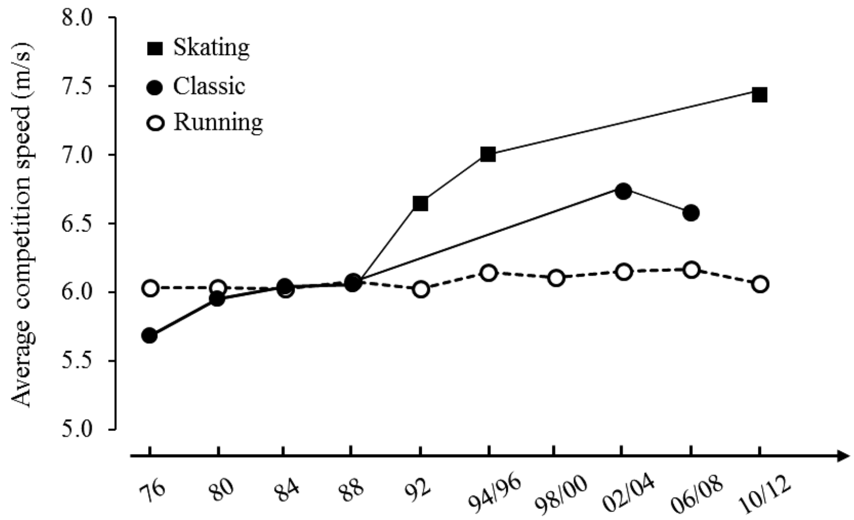

Figure 1 — Average speed for the male winners of 15-km cross-country skiing and 10,000-m running during Olympic competitions from 1976 to 2012. Note that 15-km cross-country skiing was performed as a pursuit race, with a starting procedure based on the result the previous day, between 1992 and 1998. Here only the races in 1992 and 1994 are included since the winner of the 1998 race had especially slow snow conditions and advanced in the field during the race, making a comparison with the other competitions invalid.

involve mass starts, where tactics are more important than previously and the outcome is often decided in the final sprint. The competition terrain varies but is mandated to include approximately one-third uphill, one-third flat, and one-third downhill. This forces skiers to alter their technique often. However, more than 50% of the racing time is spent on the uphill sections, which is where individual performance variation is greatest.[1,2] The aerobically derived proportion of the total energy expended during such competitions (ie, 70–75% in sprints and 85–95% across longer distances) is of course comparable to the corresponding values for other sports with similar racing times. However, XC skiers often adopt a strategy with higher intensity on uphill terrain, driving work rates considerably higher than that required to elicit maximal oxygen consumption (anaerobic proportion up to 40% during sprint races and 10–20% across the longest distances). This "pacing strategy" is achieved by utilizing downhill sections for recovery.[1,3]

Physiological Characteristics of Elite Cross-Country Skiers

World-class cross-country skiers have shown some of the highest maximal oxygen uptake (VO_{2max}) values ever reported, with values of 80 to 90 and 70 to 80 $mL \cdot kg^{-1} \cdot min^{-1}$ for men and women, respectively.[4–7] Absolute values exceeding 7 L/min have been recorded among several male medal winners (unpublished data, Norwegian and Swedish Olympic Committees). Thus, every step of the oxygen transport is being challenged, often by temperatures as low as –20°C during competitions. Exercise ventilation rates of 250 L/min,[8] blood volume of 9 L, cardiac outputs >40 L/min, and stroke volumes >200 mL[9] have all been reported among elite performers.

Today's world-class distance cross-country skiers from Norway and Sweden demonstrate aerobic capacity similar to that of previous Olympic champions. At the same time, demands on anaerobic capacity, upper-body power, high-speed techniques, and "tactical flexibility" have all increased for those aspiring to win medals. For example, in connection with sprint skiing, speed over a short distance and maximal strength correlate closely with performance.[10,11] The absolute values of VO_{2max} exhibited by elite sprint and distance skiers are similar, but the former are slightly lower relative to body mass and the sprint skiers also have higher anaerobic capacity.

In the case of both sprint and distance skiing, the ability to efficiently transform metabolic energy into speed is a key determinant of performance.[12–14] This observation probably reflects the technical complexity involved, with numerous degrees of freedom with respect to timing force generation by the arms and legs in connection with the various skiing techniques.

The Biomechanics of Cross-Country Skiing

As cross-country skiing has evolved, more and more attention is being focused on the biomechanics of performance. Cross-country skiers must master a wide range of speeds (5–70 km/h) and terrains (with inclines of –20% to 20%). To accomplish this, they continuously change among and adapt the 9 subtechniques of classical skiing and skating. During a 1.5-km sprint race, skiers change the subtechnique being employed approximately 30 times,[2] whereas across longer distances many hundreds of such transitions occur. This is unique in comparison with other Olympic sports and makes the 2 major transitions of the triathlon seem almost straightforward to study.[15]

With both the skating and classical techniques, higher speeds make greater demands on producing propulsive forces to increase cycle length. One important strategy for enhancing cycle length is more effective poling, with preactivation and stretch shortening of the muscles and active lowering of the center of mass to attain higher peak force earlier in the movement cycle.[16,17] Accordingly, more explosive techniques such as "kangaroo" double poling and double-push skating have been developed for use on flat terrain.[16,18] With such techniques, the most explosive skiers can produce peak double-poling forces as high as 430 N within a period of 0.05 seconds, as well as forces above 1600 N during the leg push-off when skating.[11] On steep uphill terrain, faster skiers increase cycle rate while maintaining cycle length, and over shorter sections innovative techniques such as "running diagonal" and "jump skate" are used to accelerate rapidly. In addition, there has recently been more and more focus on the downhill sections of a race, especially the challenging downhill turns, where faster skiers use the accelerating step-turn technique more extensively.[19]

Tactical Aspects of Cross-Country Skiing

In individual time trials, skiers work more intensely on uphill terrain, where maximal work for a given metabolic cost can be achieved.[1,20] In prolonged endurance events performed on relatively consistent terrain, even pacing is generally shown to be optimal.[21] In contrast, optimal pacing during cross-country skiing must take into account more variables, since the track profiles vary, as do snow conditions at different times during a season or even a single race. Effective pacing in connection with the Sochi Olympics will be an even greater challenge, since the higher altitude (1550 m above sea level) will limit the speed that can be attained on uphill sections, as well as recovery on downhill terrain.

Moreover, the introduction of mass start into Olympic cross-country-ski races has accentuated the importance of both drafting economically behind other skiers[22] and obtaining a position that is least problematic and allows optimal utilization of one's individual strengths. Furthermore, team tactics can sometimes provide an advantage in connection with such races. However, team tactics in cross-country skiing differ from those employed in cycling competitions, for example, due to the lower speeds involved, the narrower tracks, and the facts that only 4 skiers from each country are allowed to compete. In addition, the work rate on uphill terrain is often too demanding for the weaker skiers, making the typical "lead-out sprints" seen in cycling very rare in cross-country skiing.

Training for Olympic Cross-Country Ski Races

Endurance training has always been the major component of a cross-country skier's training. For research purposes, 3 levels of intensity (ie, low, "threshold," and high) have been defined, but for practical reasons most skiers today use 4 or 5 levels of intensity in connection with their endurance training. Based on the session-goal approach, endurance training by cross-country skiers involves a "polarized" model, with a great deal of low-intensity training and low to moderate amounts of high-intensity training.[23,24] The amount of endurance training at these different levels has apparently not changed during the past 3 decades, and skiing, roller skiing, and running on varying terrain remain the predominant modes of exercise.

However, during this same period 3 distinct developments in training have been observed:

- More training is performed on roller skis, often on special roller-ski tracks involving competition-specific terrain and techniques.
- More emphasis is placed on training both strength and endurance of the upper body.
- Skiers systematically incorporate strength, power, and speed training, especially skiers specializing in sprint racing.

Table 1 summarizes the training of Norwegian and Swedish sprint and distance cross-country skiers who have won Olympic gold medals during the past decade.

Future Perspectives

The International Ski Federation has decided to keep the current program for Olympic cross-country skiing during the next few Olympic Games, so the demands in this context will probably not change to as great an extent as in previous years. Although the physiology and biomechanics of cross-country skiers have been analyzed in detail in the laboratory in recent decades, we still know relatively little about actual competitions, which are performed outdoors at different temperatures and with a variety of snow conditions and track profiles. Recent advances in sensor technology allow the position, speed, kinematics, and kinetics of cross-country skiers to be recorded in real time on the track, thereby providing more detailed information about the factors that lead to success in the Olympic Games. Furthermore, the increased complexity of both physiological (same aerobic demands, greater anaerobic demands) and technical training (more subtechniques to master) for modern cross-country skiers increases the individual variation in how athletes adapt and respond to training. Better data from competition conditions will enhance our ability to provide specific best-practice guidelines for training future Olympic champions as a group. However, the need for research exploration that enhances precise matching of training to the unique characteristics of each individual skier will likely drive scientific innovation for years to come.

Table 1 The Training Schedules of Norwegian and Swedish Sprint and Distance Cross-Country Skiers Who Have Won Olympic Gold Medals During the Past Decade

Distance skiers	Sprint skiers
In total, 800–900 h of training per year, of which 85% was aerobic endurance training	In total, 750–850 h of training per year, of which 75–80% was aerobic endurance training
500–600 h or 300–350 sessions at low intensity (60–80% of maximal heart rate)	450–500 h or 300 sessions at low intensity (60–80% of maximal heart rate)
30–40 sessions at moderate intensity (80–90% of maximal heart rate)	25–30 sessions at moderate intensity (80–90% of maximal heart rate)
60–70 sessions per year at high intensity (>90% of maximal heart rate)	50–60 sessions per year at high intensity (>90% of maximal heart rate)
5–15 sessions of anaerobic lactacid training (high blood lactate levels)	15–25 sessions of anaerobic lactacid training (high blood lactate levels)
Systematic development of power and speed throughout the entire season, including 1 full-speed session, 2 or 3 series of short-impulse training, and 1 or 2 sessions of strength training per week	Systematic development of power and speed throughout the entire season, including 1 or 2 full-speed sessions, 2 or 3 series of short-impulse training, and 2 sessions of strength training per week
400–500 h of training with a ski-specific mode of exercise (skiing, roller skiing, running with poles)	400–500 h of training a ski-specific mode of exercise (skiing, roller skiing, running with poles)
Equal focus on training on steep, flat, and varied terrain	Emphasis on training on flat and varied terrain

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