NORDIC SKIING BIOMECHANICS AND PHYSIOLOGY

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Cross-country skiing provides unique movement patterns and unique athletes for sport science research. The integration of physiology and biomechanics into research projects has provided insights into systemic solutions regarding high intensity, whole body exercise and how workload is distributed. Newly introduced ski sprint events have stimulated continued research to better understand performance and human capacity limitations.

KEY WORDS: aerobic capacity, cross-country skiing, energy cost, workload distribution

INTRODUCTION: In the interdisciplinary field that we today refer to as kinesiology or exercise science, there is a long historical connection to researchers in Scandinavia who used familiar modes of activity such as running, cycling and skiing in their physiological and biomechanical experiments. Early in the 20th century, field measurements of metabolic costs were documented for a variety of forms of locomotion including cross-country skiing (e.g. Liljestrand & Stenström, 1920). Later, Christensen and Högberg (1950) documented an oxygen uptake of 5.2 $L \cdot min^{-1}$ in a skier. More recently, the widely read *Textbook of Work Physiology* by Åstrand and colleagues (original edition in 1970) included an illustration of a skier with a Douglas bag on his back during oxygen uptake measurements while cross-country skiing. These and many other examples from Scandinavian researchers form an important core in the entire exercise science literature and included measurements from skiers not for convenience but because of the unusual physical capacities of the athletes involved in ski racing, the unique quadripedal characteristics of the movement patterns of skiing, and because understanding physiological and biomechanical responses in skiing can teach us much about human physiology, mechanics, and motor control more generally. It is in that spirit that this symposium presents an interdisciplinary perspective on "Nordic" skiing—an activity that has evolved considerably over the decades but which continues to provide insights into human systems.

While ski artifacts date back several millennia in northern regions with long winters, it is over the last few centuries that substantial changes have been made to ski design (Figure 1). Formenti et al. (2005) have documented the evolution of ski construction and re-created representative models of skis for usage testing under controlled conditions. Their testing showed the substantial decrease in metabolic cost per meter of skiing that has been achieved through equipment adaptations (Figure 2). This is partly due to reductions in the mass of the equipment (about 6 kg vs. 2 kg for modern skis, bindings, boots and poles) but perhaps primarily due to reductions of the coefficient of friction of skis on snow (μ of about 0.05 vs. 0.01 for modern skis on a packed snow surface, Formenti et al., 2005). These measurements were made under controlled snow conditions. In typical loose snow field conditions, it is likely that both frictional forces and metabolic costs would be substantially greater. This can be observed in the work of Christensen and Högberg (1950) where the results can be manipulated to determine metabolic cost per meter of travel (about 5 J/kg/m compared with about 3 J/kg/m measured by Formenti et al. for a packed and mechanically prepared snow surface).

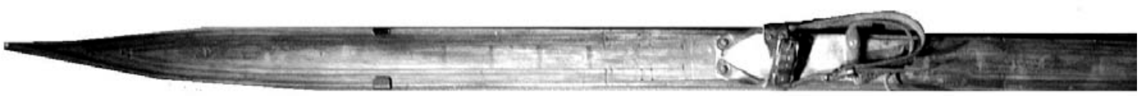


Figure 1. By the late 1800s, ski equipment had evolved from the rudimentary wooden planks of previous millennia to more refined and lighter structures. This example from the Oslo Ski Museum was thinly carved and used well developed leather bindings, but was several times the weight of modern skis.

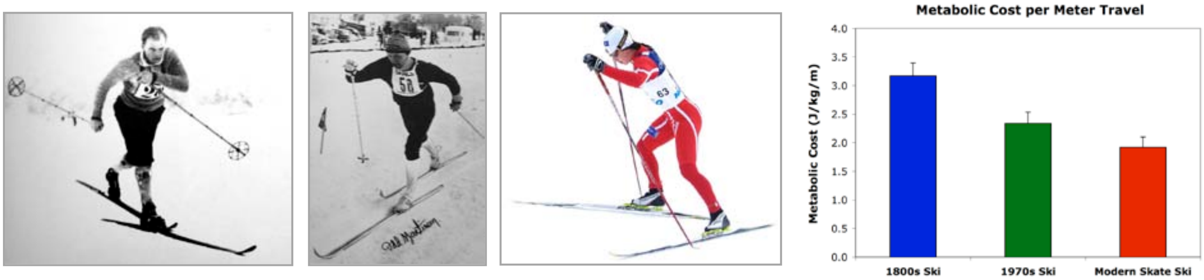


Figure 2. Equipment, ski techniques, and metabolic costs have evolved over the past century. The photos show Norwegian national and Olympic champions from the 1920s (Torleif Haug), from the 1970s (Odd Martinsen) and the 2000s (Marit Bjørgen). The relatively heavy wooden skis that Haug used were supplanted by lighter wood laminates that Martinsen raced on and later by fiberglass skis which could be optimized for skating (shown in the photo) or for classical techniques similar to Haug or Martinsen's technique of earlier years. Metabolic cost per meter of skiing on such equipment has systematically decreased over time. Photos of Haug and Martinsen were adapted from displays at the Oslo Ski Museum. Metabolic cost data are from Formenti et al. (2005).

Much of the early research using cross-country skiers was aimed at achieving better understanding of the physiological characteristics of athletes and the demands of various forms of exercise. As the sport itself has evolved, considerably more attention has been focused on technical aspects of ski performance. The new skating techniques which were introduced about 1985 have continued to evolve and provide a challenge to optimization of race performance. One emphasis of recent biomechanical studies has been to better understand the differing whole body workload distributions of various ski techniques. Studies of the interaction of human physiology with the mechanical demands of varying techniques has enhanced our understanding of how human systems respond to competing requirements from upper and lower extremities during high intensity ski racing. Recent biomechanical and physiological research lines are described below.

BIOMECHANICS OF NORDIC SKIING: Biomechanics research in sport often follows a trajectory from simple kinematic studies during early years to more complex three-dimensional kinematic analysis and finally to kinetic analyses involving measurement of force or determination of mechanical energy characteristics. Ski biomechanics research has paralleled this path in some respects but has also diversified in unexpected ways as the sport has evolved new techniques and new sprint events. In recent papers one can find examples of rather simple two-dimensional kinematic analysis combined with complex physiological and kinetic measurements integrated together (e.g. Zory et al. 2010). The complexity of field measurements has often demanded some simplification to the instrumentation. Few studies (Smith, 2000) have managed three-dimensional motion analysis combined with force measurement on snow. The result of this technical challenge is that we have very poor estimations for the various ski skating techniques regarding the components of force generated by skis and poles on snow.

Laboratory studies using rollerskis on large treadmills and full motion analysis systems have in part reduced this shortcoming. Under such controlled conditions, comparisons of skating techniques can be made which help explain technique choices for submaximal speeds (Figure 3). Unfortunately, sprint ski skating (Figure 4) has been too challenging to attempt on a treadmill, so we cannot explain in force component terms the observed performance characteristics.

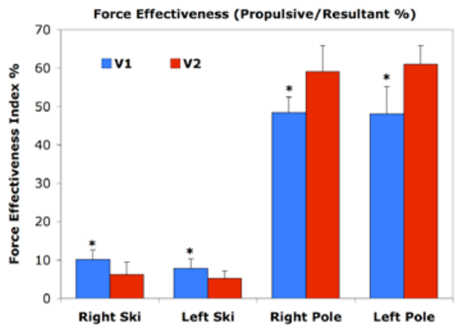
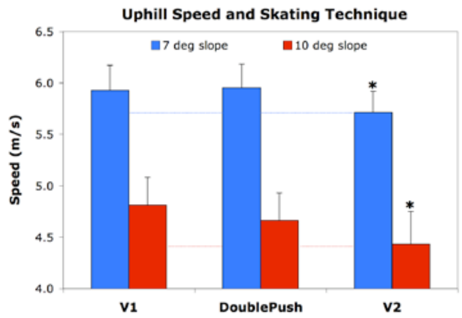


Figure 3. Force effectiveness index for skis and poles on a 5° slope. V1 ski forces were more effective than V2 while V1 pole forces were less effective ($p<0.05$). Data from Smith et al. (2009).



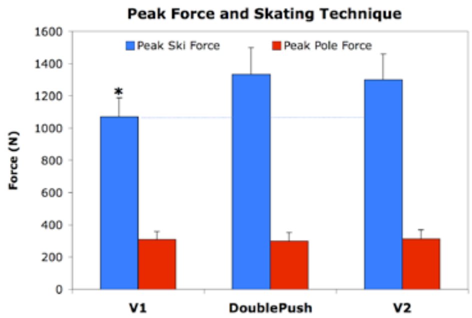


Figure 4. Uphill sprint speed and peak forces for commonly used V1 and V2 skating techniques and a newly developed doublepush technique. On uphill terrain, the V2 technique was slower and required generation of greater skating forces than V1. The new double-push technique was equally fast as V1 but required a complex ski hop maneuver and higher skating forces. Data are from Stöggl et al. (2010). * $p < .05$

PHYSIOLOGY OF NORDIC SKIING. Cross-country skiing is one of the most demanding endurance sports. It imposes extensive physiological challenges due to the multiple changes between, and utilization of, different skiing techniques, each involving the upper and lower body to various extents. The uniqueness of the sport has contributed to significant interest from researchers in sport science due to their ambition to understand more about the limiting factors of performance. Compared to other endurance sports, cross-country skiing is a complex racing form with a comprehensive diversity of locomotion types on various types of terrains and different inclinations. This indicates that, in comparison to other endurance sports, the skier's aerobic capacity in several techniques is critical for performance.

As early as in the beginning of the 20th century, Liljestrand & Stenström (1920) carried out intensive research which included not only pulmonary oxygen uptake but also determinations of cardiac output. One of the conclusions Liljestrand and associates reached was that in subjects who were studied in several different forms of locomotion the highest oxygen uptake was always found when skiing. Maximal cardiac outputs in excess of 40 $L \cdot min^{-1}$ and stroke volumes over 200 ml have been measured in elite cross-country skiers, with maximal oxygen uptake values above 6 $L \cdot min^{-1}$ (Ekblom & Hermansen, 1968) with relative values in the range of ~80-90 $ml \cdot kg^{-1} \cdot min^{-1}$ (Bergh & Forsberg, 1992). Partitioning aerobic energy costs for various regions in the body is more difficult. Modern techniques such as PET (Positron Emission Tomography) or MRI (Magnetic Resonance Imaging) to study the metabolic response or blood flow of specific muscles can be performed at least for some muscles but only for simple and well standardized muscle contractions rather than in composite movements as in cross-country skiing.

To get a more complete picture of the energy costs, traditional techniques using measurements of regional blood flow have to be performed and combined with arterio-venous (a-v) differences over the region under study. Only in cross-country skiing exercise have investigations been completed by our research group in order to analyze metabolism and aerobic energy turnover for arms and legs separately (Calbet et al., 2004; Calbet et al., 2005). During submaximal diagonal skiing, double poling, and leg skiing, cardiac output (26-27 $L \cdot min^{-1}$), mean blood pressure (~87 mm Hg) and systemic vascular conductance, systemic oxygen delivery and pulmonary VO_2 (~4 $L \cdot min^{-1}$) attained similar values regardless of exercise mode. However, distribution of cardiac output (Figure 5) was modified depending on the musculature engaged in the specific

Figure 5. For skiers at the highest intensities, the cardiovascular system must distribute blood flow and hence oxygen delivery in a manner which avoids systemic hypotension.

skiing technique. Skeletal muscle vascular conductance was restrained during diagonal skiing to maintain the arterial pressure during exercise and avoid hypotension.

A new racing form in competitive cross-country skiing is the sprint event in which skiers perform four separate races of 1200–1800 m (racing times from 2 to 4 min), starting with an individual time-trial qualification round, and thereafter heats based on a knock-out system. A relevant question is whether aerobic capacity is also of importance in such sprint races?

In a recent study that investigated the physiological characteristics of eight world-class (WC) and eight national-class (NC) Norwegian sprint cross country skiers (Sandbakk et al., 2010), the WC skiers showed an 8% higher VO_2peak than the NC skiers. In addition they reached a VO_2 plateau time nearly twice that of NC skiers, had a higher gross efficiency and 8% higher peak speed. These results indicate that aerobic capacity can differentiate between sprint skiers of different performance levels. Moreover, efficiency and the ability to reach high skiing speed is crucial for performance supporting the importance of ski technique.

SUMMARY: Cross-country skiing is both mechanically and physiologically complex. The main freestyle and classical styles, are subdivided into nine different sub-techniques. Skiers adapt to changes of inclination and speed through changes in pole and leg kinematics, kinetics, and workload distribution which affect physiological characteristics throughout the body. To achieve a better understanding, the use of an integrative biomechanical and physiological approach is an important tool for increasing knowledge and enhancing performance.

REFERENCES

Bergh, U., & Forsberg, A. (1992). Influence of body mass on cross-country ski racing performance. *Medicine & Science in Sports & Exercise*, **24**, 1033-1039.

Calbet, J. A., Holmberg, H.-C., Rosdahl, H., van Hall, G., Jensen-Urstad, M., & Saltin, B. (2005). Why do arms extract less oxygen than legs during exercise? *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, **289**, R1448-1458.

Calbet, J. A., Jensen-Urstad, M., van Hall, G., Holmberg, H.-C., Rosdahl, H., & Saltin, B. (2004). Maximal muscular vascular conductances during whole body upright exercise in humans. *Journal of Physiology*, **558**, 319-331.

Christensen, E. H., & Högberg, P. (1950). Physiology of skiing. *Arbeitsphysiologie*, **14**, 292-303.

Ekblom, B., & Hermansen, L. (1968). Cardiac output in athletes. *Journal of Applied Physiology*, 25, 619-625.

Formenti, F., Ardigó, L. P., & Minetti, A. E. (2005). Human locomotion on snow: Determinants of economy and speed of skiing across the ages. *Proceedings of the Royal Society, Biological Sciences*, **272**, 1561-1569.

Liljestrand, G., & Stenström, N. (1920). Respirationsversuche beim gehen, laufen, ski- und schlittsschuhlaufen. *Skand Arch Physiol*, **39**, 167-206.

Sandbakk, Ø., Holmberg, H.-C., Leirdal, S., & Ettema, G. (2010). Metabolic rate and gross efficiency at high work rates in world class and national level skiers. *European Journal of Applied Physiology*, DOI: 10.1007/s00421-010-1372-3.

Smith, G. A. (2000). Cross-country skiing: Technique, equipment and environmental factors affecting performance. In V. Zatsiorsky (Ed.), Biomechanics in Sport. IOC Encyclopedia of Sports Medicine Series (pp. 247-270). Oxford: Blackwell Science.

Smith, G., Kvamme, B. & Jakobsen, V. (2009). Effectiveness of ski and pole forces in ski skating. In E. Müller, S. Lindinger & T. Stöggl (Eds.), Science and Skiing IV (pp. 647-656). Maidenhead: Meyer & Meyer Sport UK.

Stöggl, T., Kampel, W, Müller, E., & Lindinger, S. (2010). Double-push skating versus V2 and V2 skating on uphill terrain in cross-country skiing. *Medicine & Science in Sports & Exercise*, **42**, 187-196.

Zory, R., Vuillerme, N., Pellegrini, B., Schena, F. & Rouard, A. (2009). Effect of fatigue on double pole kinematics in sprint cross-country skiing. *Human Movement Science*, **28**, 85-98.

Åstrand, P. O., & Rodahl, K. (1970). *Textbook of work physiology*. McGraw Hill.