Comparison of physiological and perceptual responses to upper-, lower- and whole-body exercise in elite cross-country skiers

ABSTRACT

The primary purpose of the present study was to compare physiological and perceptual responses to maximal and submaximal exercise between upper-, lower-, and whole-body exercise modes in elite cross-country (XC) skiers. Twelve elite XC skiers performed 5-7 submaximal 5-min stages and an incremental test to exhaustion using upper-body poling (UP), running (RUN) and diagonal roller skiing (DIA), randomized on three separate days. Here, power output, cardiorespiratory variables, heart rate (HR), blood lactate concentration (BLa) and rating of perceived exertion (RPE) were determined. Peak power output increased gradually from UP to RUN and DIA, whereas peak oxygen uptake (VO_{2peak}), peak HR, O_2pulse and total RPE were clearly lower in UP than RUN and DIA ($P<0.05$). At submaximal workloads matched for either RPE, %HR or BLa, the main pattern was that BLa was higher and VO_2 and HR lower in UP compared to RUN and DIA ($P<0.05$). DIA showed ~10% and 35% higher VO_2 than RUN and UP at RPE 10-13, and had lower muscular RPE values than UP and RUN at a given % of peak HR ($P<0.05$). Most of the differences in cardiorespiratory variables between modes were eliminated when they were normalized to VO_{2peak} or peak HR in the respective mode. Due to the low power production in UP, endurance training in this mode exhibits too low values of VO_2 to tax the cardiovascular system sufficiently. In RUN and DIA, the similar VO_{2peak} values indicate that both modes can be effectively used during high-intensity training and to determine VO_{2max} in elite XC skiers. However, the relatively high VO_2 values at low perceptual stress with submaximal DIA indicate that the large amount of power produced when combining upper- and lower-body work exhibits high oxidative flux even during low intensity training. Overall, these findings should be taken into account when athletes and coaches are monitoring and prescribing training in future approaches, in particular in sports where athletes varies between training with upper-, lower- and whole-body exercise modes.

KEY WORDS: Blood lactate concentration, cross-country skiing, diagonal technique, double poling, heart rate, oxygen uptake, rating of perceived exertion, running.

INTRODUCTION

Cross-country (XC) skiing involves long-lasting competitions on varying terrain whilst employing different sub-techniques of the classical and skating styles. Endurance training is the major component of an elite XC skier's 800-950 hours of annual training, and the 700-850 hours of endurance performed by the best skiers include approximately 70-80% of sessions at low-intensity, whereas around 20% are at moderate- to high-intensity (14, 29, 30). This training is distributed across various training modes, including a variation of classical and skating sub-techniques that load the upper- and lower body to different extents. Thus, XC skiers must be aware of not only the mode and intensity of their exercise, but also how they load the whole body, upper and/or lower limbs while training.

The maximal or peak capacities reached in these different exercise modes set the upper limit of exercise responses. World-class XC skiers exhibit some of the highest of maximal oxygen uptake (VO_{2max}) values ever reported, with values of 80-90 and 70-80 $mL \cdot kg^{-1} \cdot min^{-1}$ being common for the best men and women, respectively, with diagonal skiing (DIA) and running (RUN) (8, 16, 26, 35). Hence, the cardiorespiratory system is fully taxed with leg and whole-body maximal exercise. However, the corresponding values are clearly lower in techniques where upper-body work is pre-dominant (9, 21). For example, male and female elite XC skiers attain 76% versus 67% of their VO_{2max} with isolated upper-body poling. This implies peak "upper body" VO_2 values of > 60 and close to 50 $mL \cdot kg^{-1} \cdot min^{-1}$ in men and women, respectively (8).

Organizing endurance training intensity into specific training zones, based on ranges of percent of maximum heart rate (HR), percent of VO_{2max} and absolute blood lactate concentration (BLa) is common in most endurance sports (32-34), although in practice endurance athletes most often use perceptual responses (e.g. rating of perceived exertion, RPE) to decide their training intensity (4). However, the physiological responses both to maximal work and to submaximal work at given training intensity might differ substantially between exercise modes, and depending on whether athletes use HR, BLa and RPE to determine exercise intensity within these modes.

Most of the training by XC skiers are at low- and moderate endurance intensities, where the submaximal responses to lower-body (1-3, 7, 19) and whole-body (6, 11, 15, 22, 23, 36) exercise modes have been repeatedly examined. For example, a recent rowing study compared whole body exercise (rowing) with leg-dominant exercise (cycling), where cycling produced greater power outputs due to better mechanical efficiency but the main physiological responses were the same across modes. However, comparable information is limited for upper-body exercise (4, 11), although a more comprehensive understanding would indeed assist in the functional evaluation and prescription of training with different exercise modes. Due to the lower amount of muscle mass and lower peak cardiorespiratory capacities with upper-body work it is likely that the submaximal responses will be correspondingly lower than for lower- and whole-body modes. However, whether the same responses differ when normalized to the peak values in the respective mode is currently unknown, although several factors suggest that it may be the case. For example, arm muscles rely more on carbohydrate oxidation during exercise, regardless of training status in the limbs (12), and have a higher fast-twitch fiber content compared to the lower-body (17, 24). Since lactate is mainly produced in fast-twitch fibers and the uptake and oxidation of lactate mainly occurs in slow-twitch fibers (5), this might influence submaximal BLa responses even in highly upper-body trained endurance athletes such as XC skiers.

The primary purpose of the present study was to compare physiological and perceptual responses to maximal and submaximal exercise between upper-, lower-, and whole-body exercise modes in elite XC skiers. Experimentally, we compared upper-body poling (UP) to running (RUN) and diagonal skiing (DIA) and hypothesized that VO_{2peak} would be higher in RUN and DIA compared to UP, and that BLa values would be higher and cardiorespiratory responses lower with UP at submaximal intensities matched for RPE, HR or BLa.

METHODS

Experimental approach to the Problem

In order to compare physiological and perceptual responses to upper-, lower-, and whole-body maximal and submaximal exercise in elite XC skiers, we compared the maximal and submaximal responses to UP, RUN and DIA randomized on three different days. Thus, in each mode all participants performed 5-7 submaximal 5-min stages and an incremental test to exhaustion where power output, cardiorespiratory variables, HR, BLa and RPE were determined.

Participants

Twelve elite male XC skiers were recruited for participation in the study. The inclusion criteria were set to VO_{2peak} above 70 ($mL \cdot min^{-1} \cdot kg^{-1}$) in diagonal skiing, and participating in World Cup races, or other high ranked FIS-races in the 2015/16 season. The skier's characteristics are shown in Table 1. The study was approved by The Norwegian Data Protection Authority and conducted in accordance with the Helsinki Declaration.

Equipment

DIA and RUN was performed on a 5 x 3 m motor-driven treadmill (Forcelink B.V., Culemborg, Netherlands). The treadmill belt consisted of non-slip rubber surface, allowing the participants to use their own poles with special carbide tips while roller skiing. In order to minimize variations in roller resistance, the participants used the same pair of classic roller skies with standard category 2 wheels (IDT Sports, Lena, Norway). Rolling friction force (F_f) was tested with a towing test previously described by Sandbakk et al. (30) and demonstrated an average friction coefficient of 0.0195, which was included in the calculation of power output. UP was performed using the double poling movement while sitting on an adjustable bench (fixed ice sledge hockey seat) placed in front of a modified Concept2 SkiErg (Morrisville, Vermont, US) resistance level set to 5. The backrest was at ~ 120° angle. The participants sat with ~ 90° angle at the knees and were strapped in the seat around the pelvis and thighs, the pelvis region could then function as the final body segment mechanically linked to the surroundings.

This was done to avoid additional power contribution from the lower extremities (10, 11). Power output during DIA and RUN was calculated according to previous calculations of Sandbakk et al. (28) and UP according to Hegge et al. (11).

HR was recorded with Polar m400 (Kempele, Finland) and cardiorespiratory variables were measured with open-circuit indirect calorimetry using an Oxycon Pro apparatus (Jeager GmbH, Hoechberg, Germany). The instrument was calibrated against ambient air and commercial gas (Riessner Gase, Lichtenfels, Germany) with known concentrations of O_2 (16.00%) and CO_2 (5.85%) before each test session. The O_2 and CO_2 concentrations of room-air were measured and the flow transducer was calibrated using a 3–L High-precision calibration syringe (Calibration syringe D, SensorMedics, Yorba Linda, CA). BLa were measured using Biosen C-line Sport lactate measurement system (EKF Industrial Electronics, Magdeburg, Germany) collecting 20µL blood form the fingertip. The device was calibrated every 60 min with a 12 $mmol \cdot L^{-1}$ standard concentration. RPE was determined using the Borg Scale (4) for total, ventilator and muscular effort, in which the athletes rated their overall effort first, before we asked them to specifically rate their muscular and ventilatory effort. The differences between these three measures were verbally explained at the beginning of each test day. Body composition was assessed using dual-energy X-ray absorptiometry (DXA model Discovery A, Hologic, Marlborough, MA). Whole-body values were presented as total mass (kg), relative percentage of fat (%) and lean body mass, upper- and lower-body (kg).

Procedures

Following standardization of time of day, pre-test diet and pre-test exercise training, all test days were initiated with a warm-up period of 10 min at an intensity of 6-8 RPE, followed by five to seven 5-min submaximal stages at gradually increased intensity. For RUN, the starting speed was 7.5 or 8.5 km/h at a 10.5% incline, which increased every stage with 1 km/h. For UP, a power output that corresponded to an RPE of 8 was used on the first stage, followed by 20 Watt increase for each stage. In DIA, 8 or 9 km/h at 12% incline was the starting speed, which was increased by 1 km/h every 5-min stage. HR was recorded continuously during each stage and the average of the last 30 sec of every workload determined HR for the given stage. Cardiorespiratory variables were measured during the last 2 min of each stage and the average values were taken to further analyses, whereas BLa and RPE were determined immediately after every stage. When BLa reached above 6 mmol·L^{-1}, the submaximal test was ended, and the participants received an active rest period of 10–15 min until the BLa was below 3 mmol·L^{-1} before performing the incremental test to exhaustion.

An incremental protocol with increased workload every minute until voluntary exhaustion, for determination of peak power output and VO_{2peak}, was employed for all modes. The participants started at the speed/power output where they rated 12 in RPE at the submaximal test, and increased workload by 1 km/h (RUN and DIA) or 20 watts (UP) each minute until failure. Achievement of VO_{2peak} was accepted when O_2 uptake leveled off and when a respiratory exchange ratio (RER) above 1.05 was present. The average of the three highest consecutive 10-sec recordings during the last min determined VO_{2peak} and corresponding peak cardiorespiratory parameters, whereas the highest 5-sec HR measurement determined HR_{peak}. BLa and RPE were determined immediately after each test. VO_{2max} and HR_{max} were defined as the highest values reached for each individual during the incremental tests, independent of test mode.

Statistical analysis

All data were tested for normality using a Shapiro-Wilk test and are presented as mean ± SD. We analyzed responses at given RPEs, % of HR_{max} and HR_{peak} and at 2 and 4 mmol·L^{-1} BLa by using linear interpolation across the measured values for each participant. We employed a one-way ANOVA to compare peak responses between the three modes, and a two-way repeated-measures ANOVA (mode x intensity) was applied to look for global differences between the two or three different submaximal intensities (based on RPE, $\%HR_{max/peak}$ and BLa) and the three modes, as well as their interactions. In all cases, pairwise differences between the various conditions were identified with a paired samples *t* test. Alpha values of < 0.05 determined the level of statistical significance. All statistical analyses were performed using IBM SPSS Software for Mac, Version 21.0 (SPSS Inc., Chicago, IL).

RESULTS

Production of peak power output increased gradually from UP to RUN and DIA, whereas VO_{2peak}, HR_{peak}, peak O_2pulse and peak RPE (total and ventilatory) were all clearly lower in UP than the other two modes (all $P<0.05$; Table 2 and Figure 1). There were no statistical differences in the peak values of respiratory exchange ratio (RER), BLa or muscular RPE between the three different exercise modes (Table 2).

At submaximal workloads matched for either RPE, $\%HR_{max}$, HR_{peak} or BLa, the main pattern was that BLa was consistently higher and VO_2, HR and other cardiorespiratory responses lower in UP compared to RUN and DIA (all $P<0.05$; Tables 3-5 and Figure 2). Although absolute VO_2 and HR in UP were consistently lower than for RUN and DIA ($P<0.001$), the corresponding differences did not differ between modes when they were presented relative to VO_{2peak} or HR_{peak} (Figure 2). DIA showed ~10% higher VO_2 than RUN at RPE 10-13 ($P<0.05$), with RUN and DIA having approximately 25% and 35% higher VO_2 values than UP at the different submaximal loads matched for RPE (all $P<0.001$; Table 3 and Figure 1). At a given % of HR_{max}, all RPE values indicated that UP led to harder effort than RUN and DIA (Table 4), whereas DIA had lower muscular RPE values than UP and RUN at a given % of HR_{peak} ($P<0.001$; Table 5). There were lower RPE values at a given BLa value (i.e., 2 and 4 mmol/L) for UP compared to RUN and DIA ($P<0.01$; Table 6).

DISCUSSION

The primary purpose of the present study was to compare physiological and perceptual responses to maximal and submaximal exercise between upper- (UP), lower- (RUN), and whole-body (DIA) exercise modes in elite XC skiers. We found peak power output to increase gradually from UP to RUN and DIA, whereas VO_{2peak}, HR_{peak}, peak O_2pulse as well as the peak values of total and ventilatory RPE were all clearly lower in UP than the other two modes. At submaximal workloads matched for RPE, HR or BLa, cardiorespiratory responses and HR were clearly lower and the BLa values were higher with UP compared to RUN and DIA. DIA showed ~10% and 35% higher submaximal VO_2 than RUN and UP at the lowest submaximal workloads matched for RPE, and had lower muscular RPE values than RUN and UP at a given % of peak HR. However, most of the cardiorespiratory differences between modes were eliminated when they were normalized to VO_{2peak} or HR_{peak} in the respective mode.

Maximal capacity

The increase in peak power production by ~50% from UP to RUN, with a further increase of ~30% from RUN to DIA were expected since the athletes used sequentially more muscle mass from UP to RUN and DIA. These findings are in line with a previous study demonstrating increased power production when more muscle mass is used to generate propulsion in modes being primarily driven by upper-body work, from arm poling to upper-body poling (i.e., UP) and whole-body double poling (9). In that study, we also showed gradually increased VO_{2peak} values with added muscle mass. This was also found by Holmberg et al. (15) who demonstrated gradually increasing VO_{2peak} values when more muscle mass was utilized between exercise modes, from arm cranking, to double poling, RUN and DIA. In the current study, we found large increases in VO_2 from UP to RUN, but similar VO_{2peak} values for RUN and DIA. Overall, sufficient power production to tax the cardiovascular system maximally was not produced in UP, whereas the further increase in power output exerted by adding upper-body poling to legwork in DIA compared to RUN did not further enhance VO_{2peak} or coinciding physiological responses.

The two factors determining VO_{2peak} is the highest product of HR in combination with O_2pulse. The current study reveals that both HR_{peak} and peak O_2pulse were lower in UP compared to RUN and DIA, showing that various factors driving the cardiovascular system to its maximum is not fully utilized when exercising in an upper-body mode. Although XC skiers are highly trained in the upper-body (37), the peripheral capacity of the muscles to produce (metabolic) power may hence be the main limiting factor in upper-body exercise. This is supported by the fact that our XC skiers reported 10-20% higher peak values of total and ventilatory RPE in RUN and DIA compared to UP. In comparison, the peak values of muscular RPE were similar across the different exercise modes, indicating a high load on the smaller amount of working muscle mass in UP. In future studies, a more experimental examination of how the amount of working muscle mass versus the muscle's oxidative capacity influence the ability to utilize the full aerobic capacity during upper-body exercise should be done.

Submaximal responses

During submaximal testing matched for perceptual responses to exercise (i.e. total RPE), BLa was consistently higher in UP compared to RUN and DIA although peak BLa was similar across exercise modes. A similar pattern of higher BLa for UP was also found when the submaximal work was matched for the % of HR_{max} and % of HR_{peak}. Based on previous research, one of the most reasonable explanation for the higher submaximal BLa values observed in UP compared to RUN and DIA would be differences in substrate utilization, where the upper-body muscles are previously reported to rely on more carbohydrate oxidation during low-intensity exercise (12), and the fact that arm muscles may have a higher fast-twitch fiber content than leg muscles (11, 12, 24). However, in our study on well-trained XC skiers we found no differences in RER values between modes at the various comparisons, indicating similar relative reliance of substrate oxidation. In contrast previous findings on elite XC skiers implying that the upper-body muscles may have a higher ability to produce lactate whereas the lower-body may be able to remove lactate more effectively (36), would provide a more likely explanation for the differences between modes, which is possibly being particularly evident in the current study due to the restrained lower-body movement during UP. Thus, the leg muscles could likely not utilize lactate as substrate to the same extent in UP as during RUN and DIA. This further supports the suggestion that the central cardiovascular system is not the limiting factor during upper-body work, but rather local muscular fatigue, even for athletes who are highly endurance trained in their upper-body.

The lower VO_2 and HR values at submaximal intensities in UP compared to RUN are in accordance with previous studies comparing upper- and lower-body exercise (4, 13, 15, 18). This is likely due to less energy expenditure required and a subsequently lower autonomic activation when producing the lower power output in UP compared to RUN (and DIA in our approach). However, VO_2 and HR relative to VO_{2peak} and HR_{peak} at submaximal intensities matched for RPE did not differ between exercise modes. Overall, these findings indicate that low-intensity exercise with a smaller amount of muscle mass in UP provides high effort for local muscles, but less cardiovascular stimulus. However, when normalizing for the respective peak values these differences between modes seem to diminish, which indicates that "training intensity-zones" based on a percentage of peak capacity in the given mode may be a valid approach when prescribing training.

The present study shows that in DIA, athletes never were as low as 70% of HR_{peak} or HR_{max}, although RPE was ~10, which is regarded to be a "very light" to "fairly light" intensity. The relatively high VO_2 values at low perceptual stress with submaximal DIA further indicate combining upper- and lower-body work exhibits high power output and oxidative flux even during low intensity training. This implies that this whole-body exercise exerts a high cardiovascular stress load even when the perception of fatigue is low. Maybe the high training volumes at "low-intensity" with coinciding high cardiovascular stress in modes such as DIA have been an important stimulus for the extremely high VO_{2max} values found among elite XC skiers (8, 14, 15, 25, 27, 29, 30).

PRACTICAL APPLICATIONS

This experiment provides important insight on the diverse physiological and perceptual responses between upper-body, lower-body and whole-body exercise modes among athletes who are well-trained in all these movements, Although XC skiers do not regularly train or compete with isolated upper-body work, the current study may have important practical implications for endurance training prescription and evaluation in many Paralympic endurance athletes, but also in the case of XC skiers who often train with isolated upper-body modes while being injured or when putting extra emphasis on developing their upper-body endurance. For such cases, our findings show that endurance training in UP exhibits too low values of VO_2 to tax the cardiovascular system sufficiently, whereas the high submaximal BLa and muscular RPE at given workloads indicates that low-intensity exercise with relatively low (upper-body) muscle mass in UP provides high effort on local muscles. In RUN and DIA, the similar VO_{2peak} values indicate that both modes can be effectively used during high-intensity training and to determine VO_{2max} in elite XC skiers. However, the relatively high VO_2 values at low perceptual stress with submaximal DIA indicate that the large amount of power produced when combining upper- and lower-body work exhibits high oxidative flux even during low intensity training in this mode. Overall, these findings should be taken into account when athletes and coaches are monitoring and prescribing training in future approaches, in particular in sports where athletes varies between training with upper-, lower- and whole-body exercise modes.

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FIGURE LEGENDS

Figure 1. Peak work rate (A) and oxygen uptake (VO_{2peak}; B) obtained during incremental tests to exhaustion while upper-body poling (UP), running (RUN), and diagonal roller skiing (DIA). All values presented for the 12 elite cross-country skiers are mean ± SD

*significantly higher than UP; $P < 0.05$, #significantly higher than RUN; $P < 0.05$

Figure 2. Physiological and perceptual responses at submaximal workloads matched for rating of perceived exertion (RPE; A and B), peak heart rate (HR_{peak}; C and D), maximal heart rate (HR_{max}; E and F) and blood lactate concentration (BLa; G and H) while upper-body poling (UP), running (RUN), and diagonal roller skiing (DIA). All values presented for the 12 elite cross-country skiers are mean ± SD.

*significantly higher than UP; $P < 0.05$, #significantly higher than RUN; $P < 0.05$; †significant higher than DIA $P < 0.05$