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ORIGINAL ARTICLE

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Ski skating technique and physiological responses across slopes and speeds

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Abstract Appropriate technique choice may affect ski performance. V2 ski skating technique has in recent years become more widely applied on uphill terrain where V1 technique has typically been used. This investigation compared physiological responses of skiers using V1 and V2 techniques during uphill treadmill roller-skiing. Part 1: six skiers from B-level national ski teams participated in technique comparisons performed under six uphill conditions (3, 4, 5, 6, 7, and 8°) with speeds selected so external work was approximately constant for each slope. The 12 trials of 5-min steady-state skating were randomly distributed across two test sessions of six trials each. Heart rate (HR), oxygen consumption (VO_2), blood lactate concentration (La) and rating of perceived exertion (RPE) were measured. Part 2: 15 skiers from A-level and B-level national ski teams participated in V1–V2 technique comparison on constant slope (5°) with five speeds ranging from 2.25 to 3.25 m s^{-1}. In two test sessions of V1 or V2 skating (randomly assigned for 2 days) similar characteristics as Part 1 were measured. Across all variables consistent responses were observed for both the experimental parts. As slope increased, V2 skating became increasingly costly compared to V1 skating. At constant slope across the range of speeds, V2 was more costly than V1 skating. This suggests that it may be disadvantageous for skiers to use V2 instead of V1 skating technique on moderate to steep uphill terrain. Doing so may result in elevated HR, La, and VO_2 compared to V1 skating at the same speed.

Keywords Cross-country skiing · Skating · Economy

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Introduction

The development of ski skating techniques has led to remarkable changes in cross-country skiing due to improved equipment, trail preparation, and performance. A rapid evolution occurred when the "free style technique" became a formal component of cross-country racing in 1985. Ski skating was primarily introduced due to the greater speed that was attainable with an advantage estimated to be as much as 20% faster than classical technique (Karvonen et al. 1987, 1989; Bilodeau et al. 1991). For ski racers, speed and economy are major centers of attention which integrate physiological, mechanical and technical, factors. The close connection between performance and energy cost has been demonstrated in a number of aerobic sports (e.g., Conley and Krahenbuhl 1980; Costill et al. 1985; Coyle et al. 1991; Miura et al. 1997) and is likely an important determining factor in optimal usage of ski techniques.

A number of skating techniques (and individual variations) have developed as skilled skiers have tried out different solutions of the v skating pattern over a variety of terrain. Ski skating gives the opportunity to select between various techniques and can from this perspective be considered as a gear system (Nilsson et al. 2004). When skiing speed changes according to the terrain and conditions of the track, it is important to choose the right gear in the form of proper technique. This might influence the movement pattern, the working conditions for the musculature, and the metabolic cost (i.e., economy) of the skiing technique. Some techniques are appropriate to flat or slightly downhill terrain, while others are proper on moderate or steep uphill. The primary skating techniques include V1, V2, V2A, and free skating without poles. The *V1 technique* (also called "paddling", "offset", "gear 2" and other names) is generally considered as an uphill technique and uses both poles in an asymmetrical and asynchronous pole plant combined with a skating stroke on one side but not on the other side. In contrast, the *V2 technique* (also called "double dance", "one skate" and "gear 3") is usually viewed as a higher speed technique to be used under faster conditions on flat terrain or to maintain momentum over short uphills. It is a symmetrical skating technique utilizing a double pole plant with a skating stroke on each side.

In race conditions, it is easily observable that racers use different ski skating techniques even under similar conditions. On moderate uphills, for example where the slope might be in the region of 4–6°, some skiers use V1 technique while others use V2. On this type of incline, both techniques seem to be effective, thus there has been some debate among athletes and coaches about which technique is optimal for performance based on economy and other measures. Normally, about one third of a cross-country ski race course is uphill while approximately half of a racer's time during a competition is spent on uphill sections. For this reason, a comparison of physiological responses when using V1 and V2 on uphill slopes constitutes an important topic for understanding optimal ski performance.

Human walking and running ranges of speed overlap in a region where both fast walking and slow running can be accomplished. A speed crossover point exists, below which it is more economical to walk and above which it is more economical to run (Margaria et al. 1963). In a similar manner, it is of interest to compare V1 and V2 skating techniques in relation to physiological responses at different speeds and slopes. The examination may perhaps illustrate a difference in energy cost between these ski skating variations, and thus demonstrate a possible crossover point where one technique becomes advantageous for one or more physiological measures. As far as the authors know, no previous studies have made such comparisons across skating techniques under well-controlled conditions on a treadmill.

The aim of the present study has therefore been to compare V1 and V2 skating techniques using roller skis on a large treadmill and measuring physiological responses at different slopes and speeds.

Methods

The primary study was carried out in two parts dealing with physiological comparisons across slopes and speeds, however, skiers involved in Part 1 also underwent a pretest to determine submaximal oxygen uptake and blood lactate concentration (La) as well as peak VO_2 in ski skating.

Pre-test

Subjects of Part 1 initially went through a pretest on roller skis. Heart rate (HR), oxygen consumption (VO_2), and blood lactate were measured in three submaximal trials of 5-min duration. The trials were performed with constant speed of 3 m s^{-1} at 4, 5 and 6°, or 5, 6 and 7° according to the performance level of the skiers. During each condition VO_2 was recorded from 1.5 min to 4.5 min until a steady state was reached. Heart rate was recorded every 5 s during the whole test. Immediately after finishing every 5 min condition 50 µl of capillary blood was sampled from the fingertip. Blood lactate concentration was analyzed immediately after sampling. Trials were separated by a 2-min rest. The subjects had a longer rest to prepare for a final peak VO_2 test. The max tests started at 5 or 6° at a speed of 3 m s^{-1} and then increased with one degree for each minute of the next 2 min, and further an increase of the speed to 3.25 and 3.5 m s^{-1} for the next 2 min. If necessary, an additional increase of the velocity was carried out in order to reach the peak VO_2. This maximum test lasted 4–6 min and the end of test criteria were established by a leveling off of the oxygen uptake with increasing work load, volitional exhaustion, and a respiratory exchange ratio above 1.05. The skiers were familiar with these submax and max testing protocols from previous team testing.

Part 1

Subjects

Five Nordic combined and one biathlete from the national level B teams volunteered as subjects. Their mean characteristics were: age 21 ± 4 years, height 179 ± 5 cm, mass 68 ± 6 kg and skating peak VO_2 68.0 ± 2.9 ml kg^{-1} min^{-1} . Though relatively young males, all the subjects were highly skilled in the skating techniques of this study and experienced in ski racing. Each of the skiers was familiar with roller skiing and with skating on the treadmill. All the participants gave their informed consent and could resign whenever they felt it necessary.

Apparatus

The tests were performed on a large (3×4 m) treadmill (produced by Rodby, Sweden) with capability to change speed and inclination. The subjects used the same type of roller skis (Swenor skate with tire type 1) and poles (Swix Team RC 29) with special ferrules adapted for the treadmill surface. The treadmill rubber belt material provided sufficient resistance perpendicular to the rolling direction to perform a skating stroke easily while the rolling resistance (coefficient of friction, $\mu \approx 0.02$) was similar to previous rollerski evaluations over ground (e.g., Hoffmann et al. 1995; Millet et al. 1998b). This rolling resistance is somewhat lower than typical of skis on natural snow where temperature, snow granularity, surface preparation, and ski waxing will affect the ski drag forces. Under natural conditions, ski coefficient of friction can range between 0.02 and 0.10 or higher

(Colbeck 1994), thus, rollerski skating on the treadmill corresponded to very fast snow conditions.

Blood samples were obtained from a cleaned finger for analyzing blood lactate on a lactate analyzer (YSI 23 L Yellow Springs Instruments). Oxygen consumption was determined over 30-s intervals for each condition (Oxycon Champion). Heart rate was recorded every 5 s during the tests (Polar Sport Tester). The participants indicated their rating of perceived exertion (RPE) using a 6–20 scale (Borg 1970).

Experimental design

The experimental design involved a repeated measures comparison of physiological responses for V1 and V2 skating techniques on six uphill slopes. From repeated measures analysis of variance (RANOVA), the main effect technique and the interaction term technique*slope were used to evaluate the V1 vs. V2 comparison and whether the relationship changed with slope. In addition, the V2–V1 difference for each characteristic (expressed as percent difference relative to V2) was determined across slopes. The linear regression of percent difference vs. slope was used to determine a crossover point of relative advantage of V2 or V1 technique. The skating techniques were compared under six uphill conditions (3, 4, 5, 6, 7 and 8°) where the subjects performed a 5-min skating trial on all slopes with both V1 and V2 techniques. The speed was individualized so that the submax VO_2 was between 75% and 80% of peak VO_2. In addition, the speed was calculated for each slope to keep the external work (vertical displacement rate) approximately constant across slopes. The 12 trials were randomly distributed in two testing sessions of six trials. Each session started with an initial warm up of 15 min on the treadmill. A fingertip sampling of capillary blood (50 µl) was done before the test trials began. Blood lactate concentration was analyzed immediately after sampling. Each 5-min trial of steady skating involved a recording of oxygen uptake (from 1.5 min to 4.5 min). Heart rate was recorded every 5 s. At the end of 5 min of skating, the treadmill was stopped and 50 µl of capillary blood was sampled from the fingertip and RPE was recorded. 1.5 min after stopping, the treadmill was restarted and the subjects skated for 2 min of recovery at a slope of 3° and a speed of 2.25 m s^{-1} . Another 1.5 min was used for fingertip sampling of capillary blood for determination of La, drinking, and preparing the treadmill for the next trial. In this manner, there was a 5-min recovery between the trials.

Part 2

Subjects

Four Nordic combined skiers from the national A team, six from the national B team and five junior biathletes from the Norges Toppidrettsgymnas volunteered as subjects. The mean age for the whole group of 15 males was 20 ± 4 years, height 180 ± 5 cm and mass 71 ± 6 kg.

Apparatus

The apparatus used in part 1 was used in part 2 of the study also.

Experimental design

The experimental design involved a repeated measures comparison of physiological characteristics for V1 and V2 ski skating techniques on a fixed slope of 5° and a range of speeds. Using RANOVA, V1 vs. V2 characteristics were compared and any interaction with speed evaluated. Each subject performed two separate tests including five skating trials of 5 min for both skating techniques, doing one technique per test. The two test sessions were randomly divided in 2 days. Initial speed for each test was 2.25 or 2.50 m s^{-1} depending on the performance level of the subject and increased 0.25 m s^{-1} for each 5-min skating trial. Each session began with 15 min of warm up on the treadmill. Fifty µl of capillary blood was sampled from the fingertip and analyzed immediately to determine La before the first skating trial in the test. Then five skating conditions of 5 min were executed at controlled technique, slope, and speed. Each stage of steady-state skating involved a recording of HR (every 5 s) and oxygen uptake (from 1.5 min to 4.5 min). Immediately after the end of the 5 min the treadmill was stopped for fingertip sampling of capillary blood to be used for determination of La and RPE was recorded. At 1.5 min after stopping the subjects skated for 2 min on an incline of 3° and a speed of 2.25 m s^{-1}, followed by a new blood sample. Then the subjects were allowed to drink and the treadmill was prepared for the next interval. Accordingly there was a 5-min recovery period after each skating session.

Results

Part 1

Six subjects executed twelve randomized skating trials divided into separate exercise sessions of six trials each. Five minutes of recovery separated each trial during which blood lactate levels decreased to 1.8 ± 0.4 mM. A comparison of physiological responses of V1 and V2 technique across a range of uphills (3–8°) was carried out. VO_2, HR, lactate, and RPE responses for the roller skiing sessions are presented in Table 1. From the repeated measures ANOVA, the main effect (V1 vs. V2) was significantly different for the VO_2 dependent variable ($p = 0.03$) while for HR and La significant interactions of technique and slope were observed.

Table 1 Physiological responses (mean ± SD) to roller skiing with V1 and V2 skating techniques vs. uphill steepness

	Technique	3°	4°	5°	6°	7°	8°	RANOVA: p Technique p Tech*Slope	Regression: horizontal intercept and 95% confidence interval
VO_2 (ml kg^{-1} min^{-1})	V1	52.0 ± 2.5	54.7 ± 3.1	51.7 ± 3.0	55.5 ± 2.6	51.2 ± 4.2	51.7 ± 3.0	$p = 0.03$	3.6°
	V2	52.3 ± 1.9	54.9 ± 3.5	52.3 ± 3.5	55.8 ± 3.6	54.9 ± 3.5	54.4 ± 3.5	$p = 0.18$	NS
	Regression equation: VO2% difference = 1.16 angle–4.12 ($r = 0.77$ $p = 0.08$)								
Heart rate (beats min^{-1})	V1	174 ± 12	174 ± 10	166 ± 17	173 ± 10	169 ± 12	168 ± 8	$p = 0.22$	4.2°
	V2	171 ± 11	175 ± 11	170 ± 10	174 ± 8	175 ± 11	178 ± 9	$p = 0.04$	CI: 2.0–5.2°
	Regression equation: HR % difference = 1.40 angle–5.93 ($r = 0.92$ $p = 0.01$)								
Lactate (mmol l^{-1})	V1	2.7 ± 0.8	3.5 ± 0.7	2.5 ± 0.6	3.1 ± 0.7	2.3 ± 0.7	2.5 ± 0.6	$p = 0.22$	4.5°
	V2	2.2 ± 0.5	3.4 ± 0.5	2.9 ± 0.6	3.8 ± 0.9	3.6 ± 0.8	3.5 ± 0.7	$p < 0.01$	CI: 2.9–5.3°
	Regression equation: LA % difference = 10.31 angle–46.18 ($r = 0.94$ $p = 0.01$)								
RPE (points)	V1	14.9 ± 1.2	14.4 ± 0.9	13.9 ± 1.3	14.8 ± 1.4	14.1 ± 1.0	13.9 ± 1.0	$p = 0.11$	4.8°
	V2	13.8 ± 1.2	15.0 ± 1.6	14.0 ± 1.1	14.7 ± 1.0	15.3 ± 1.2	15.8 ± 0.8	$p = 0.16$	CI: 0.5–6.4°
	Regression equation: RPE % difference = 3.18 angle–15.33 ($r = 0.86$ $p = 0.03$)								

$n = 6$ except for 3° where $n = 5$. Repeated measures ANOVA tested technique differences (V1 vs. V2) and the Technique*Slope Interaction. Linear regression of percent difference between V1 and V2 characteristics against angle was used to predict the crossover point (horizontal intercept) of relative advantage between techniques

The response across slope was further analyzed using linear regression to evaluate each variable's percentage difference relationship to slope. The regression equations are listed in Table 1 and plotted in Fig. 1. Significant linear relationships with slope were observed for HR ($p = 0.01$), La ($p = 0.01$) and RPE ($p = 0.03$) while VO_2 percent difference changes with slope were not significant ($p = 0.08$) and exhibited nonlinear responses. The horizontal intercept of each regression line provided an estimate of where each characteristic changed from relative advantage of the V2 technique to advantage of the V1 technique. These crossover points ranged from 4.2° to 4.8°.

Part 2

Fifteen subjects carried out a repeated measures comparison of V1 and V2 ski skating techniques on a fixed slope of 5° and increasing speeds on a treadmill. While each day's overall test included five speed steps, four subjects were unable to complete the last trial at greatest speed. According to the performance level of the skiers, some started at 2.25 m s^{-1} and the others at 2.50 m s^{-1} . The results illustrated in Fig. 2 include a range of speeds from 2.25 m s^{-1} to 3.25 m s^{-1}. The collections from 2.50 m s^{-1} to 3.00 m s^{-1} were performed by all subjects and were used for the RANOVA comparisons. Respiratory Exchange Ratios (RER) across speeds ranged from about 0.95 at 2.25 m s^{-1} to 1.01 ± 0.04 at 3.25 m s^{-1} which together with the other characteristics indicates that the final speed step was equal to or greater than the typical race pace. Consistent results (Fig. 2) were observed for each variable: V2 skating had a greater VO_2, HR, lactate and RPE characteristics across the range of speeds, compared with V1 skating.

Discussion

The present study investigated physiological responses during roller skiing with V1 and V2 skating technique on a treadmill across slopes with approximately constant external work (vertical displacement rate), and on a fixed slope with increasing speed. Since the development of ski skating several investigations have examined the physiological responses for both skating and classical skiing and further compared the relative economy of these techniques (e.g., Karvonen et al. 1987, 1989; Saibene et al. 1989; Hoffmann et al. 1990, 1998; Mygind et al. 1994; Mognoni et al. 2001). Far fewer studies have done

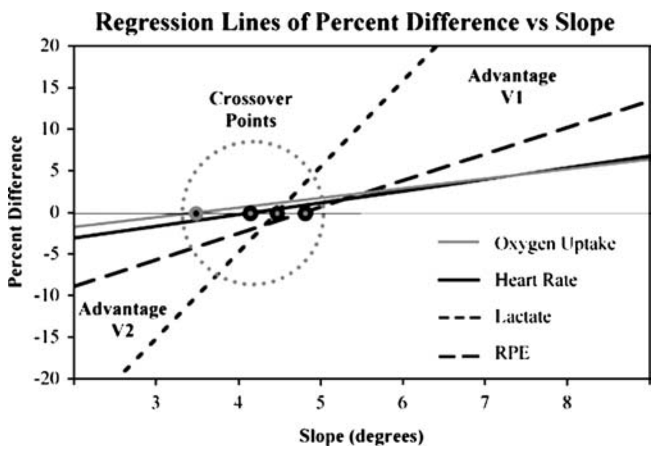

Fig. 1 V1 versus V2: Regression lines of percent difference across slopes. Significant slope was observed for heart rate, lactate, and RPE but not oxygen uptake ($p = 0.01$, 0.01, 0.03 and 0.08 respectively). From the regression equations, the horizontal intercepts were determined. These "crossover points" at 4–5 degrees, separate where it was relatively advantageous to use V2 from slopes where it was advantageous to use V1 skating technique

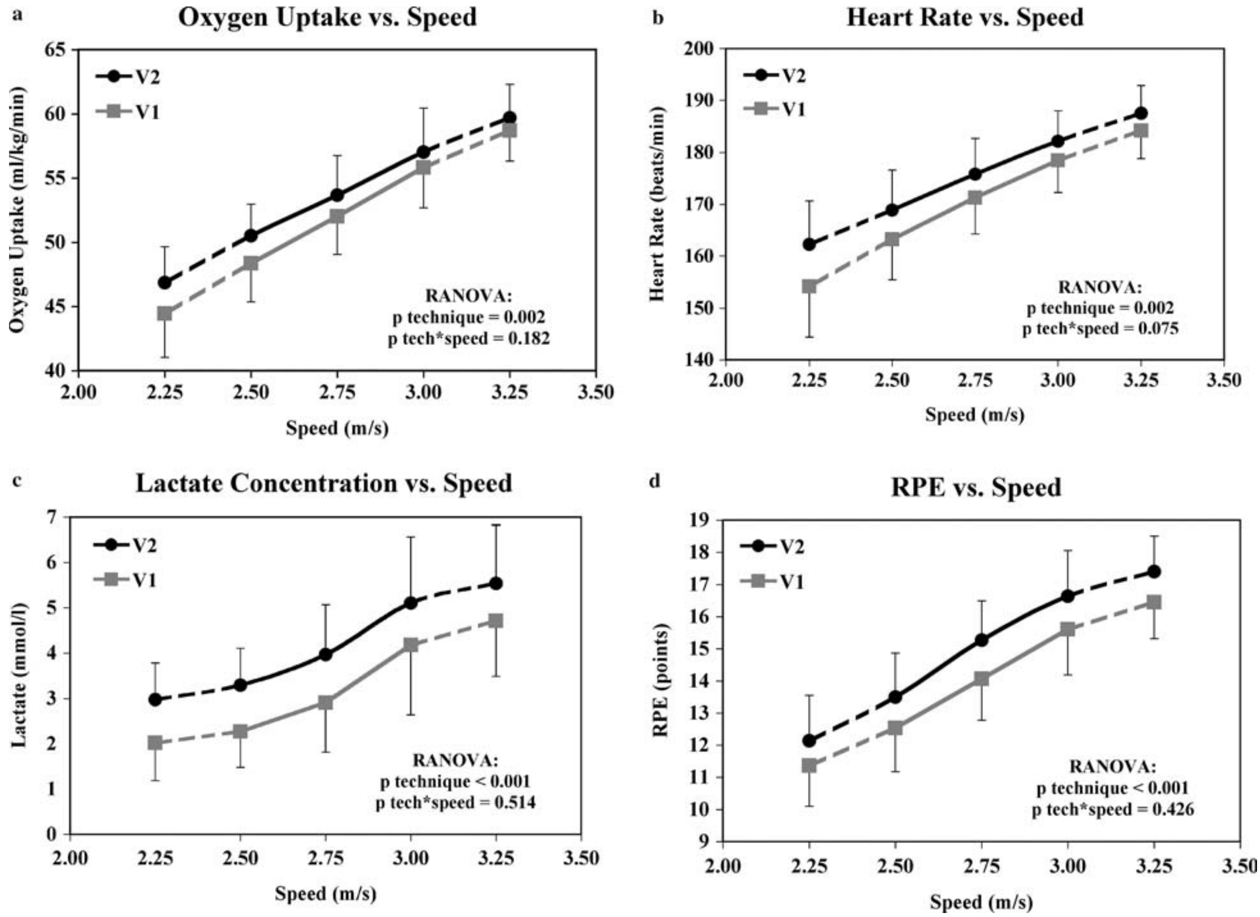

Fig. 2 V1 versus V2 skating: comparison of physiological responses across a range of speeds on a fixed slope of 5 degrees. The speed of 2.25 m s^{-1} had $n = 11$ while the speed of 3.25 m s^{-1} had $n = 10$. Other speeds (2.50–3.25 m s^{-1}) were completed by all skiers ($n = 15$). Based on repeated measures ANOVA, significant differences of the main effect (V1 vs. V2 technique) were observed for oxygen uptake (**a**), heart rate (**b**), blood lactate concentration (**c**) and rating of perceived exertion (**d**). Error bars are SD across subjects

skating technique comparisons of physiological responses (e.g., Hoffmann and Clifford 1990; Bilodeau et al. 1991; Boulay et al. 1994; Millet et al. 2003). Thus, little evidence exists providing a physiological basis for technique selection for skating on diverse terrain. Therefore, an examination and comparison of physiological responses of V1 and V2 skating may be quite helpful since it is observable in race situations that these techniques are frequently used under similar conditions.

The present study was carried out with roller skis on a large treadmill. Even though skiers perform their sport on snow, most published data on economy and metabolic responses of different skiing techniques originated from roller-skiing studies (e.g., Hoffmann et al. 1990, 1994; Mittelstadt et al. 1995; Millet et al. 1998a; Perrey et al. 1998; Mahood et al. 2001). Reported variables measured during roller skiing have been strongly correlated with on-snow skiing performance (Rundell 1995; Mahood et al. 2001; Millet et al. 2002). Roller skiing is furthermore an important training method during dry-land training in cross-country skiing. Roller ski studies may therefore play an important role for observing different aspects of ski technique and giving useful training suggestions for skiers.

Part 1

Physiological responses on varying slopes

In the present investigation, VO_2 responses for V1 and V2 technique were significantly different across slopes ($p = 0.03$) while the interaction was not significant. The pattern of VO_2 consumption in the present study suggests a similar energy cost for V1 and V2 skating on smaller inclines, but on steeper uphills, V1 has a clear advantage. Little data exist comparing VO_2 responses between V1 and V2 skating techniques. One of the first investigations to measure and compare VO_2 between skating techniques was done by Hoffmann and Clifford (1990) which was carried out on level snow terrain and compared physiological responses elicited by classical, marathon skate, and V1 skate techniques. In that study, the skating techniques induced similar VO_2 and HR responses. Millet et al. (2003) compared V1, V2, V2A, and free skating without poles on level snow terrain and reported a significantly lower energy cost for V1 technique compared to V2. Under the conditions of that study, V2 had no advantage compared to V1 with reference to VO_2. Results of our study suggest little difference of VO_2 responses between V1 and V2 techniques on lower inclines, though we did not evaluate skating on slopes less than 3°. However, it should be noted that other characteristics (HR, lactate, RPE) were consistently trending higher for V1 at the 3° condition, perhaps indicating a lower limit of slope for an effective V1 technique.

Few existing studies have compared physiological responses to different skating techniques on *uphill* terrain. One previous investigation (Bilodeau et al. 1991) compared HR response and skiing speed between V1, V2, and V2A skating techniques on snow with elite skiers at race speed around a 3-km track of varying terrain. No significant differences were found in HR values and velocities between the skating techniques on any sections of the course. It should be noted that each section of the course was rather short, and may not have been long enough to distinguish between techniques. Boulay et al. (1994) compared V1, V2, and Gunde skate (V2A) across slopes (−1, 0, 6, 9, and 12%) with respect to maximal velocity over a short distance on snow. V1 was significantly faster on the two steepest slopes. Heart rate was the only physiological response measured and demonstrated a significant increase with increasing slope for Gunde (V2A) and V2 but not V1 skating. V1 showed slightly lower values for HR on the two steepest slopes compared to V2. Millet et al. (2003) found the HR responses to be significantly lower for V1 compared to V2 on level terrain on snow.

In the present investigation, HR responses to technique had a significant interaction with slope ($p = 0.04$) which was reflected in the significant linear regression ($r = 0.92$). On the lower slopes, only small differences between the techniques were observed with V2 having the lowest HR values on the smallest incline. These results confirm the consideration of V1 skating as an uphill technique, and V2 as a high speed technique with some disadvantage on steeper uphills where V2 HR was higher than V1 HR at the same speed.

Blood lactate concentration during endurance exercise is a variable which may negatively affect performance (Lafontaine et al. 1981). Thus, a lower La when using either V1 or V2 skating might be a physiological rationale for technique choice. To our knowledge no studies have been published which compare La during V1 and V2 skating. In somewhat comparable work, Mygind et al. (1994) examined La during skating and classic skiing throughout two simulated races. They found La to be lower during classical skiing compared to skating. In the present study, a significant technique*slope interaction was observed where V1 technique elicited relatively lower lactate accumulation in the blood as the incline increased compared to V2, while V2 had lower La on low angled slopes. This relationship was reflected in the significant regression ($r = 0.94$) of lactate percent difference with slope.

Based on these consistent observations with VO_2, HR, and La, it is questionable how appropriate it is to use V2 technique on longer uphills composed of slopes greater than 5° since the consequence appears to be greater lactate accumulation in the blood compared with V1 skating at the same speed. For example at 8° the lactate concentrations were 2.5 vs. 3.5 mM for V1 and V2 techniques, respectively. Such a difference in the lactate response could be a determining factor in whether a skier reaches a "break point" for onset of blood lactate accumulation by influencing the balance between lactate formation and clearance in the musculature and blood (Jones and Ehrsam 1982; Karlsson and Jacobs 1982). If the work rate exceeds such a threshold, a progressive increase in blood lactate will occur and the exercise will be difficult to continue for more than a few minutes as active muscle force generation reaches limitations.

The apparent disadvantage of V2 technique on slopes above 5° was observed in this study with relatively young, national level skiers (mainly Nordic combined discipline) and not senior, A-level cross-country or biathlon skiers. Recent treadmill economy tests (unpublished data) with four senior level international skiers found elevated VO_2, HR, and lactate responses for V2 compared to V1 skating on slopes of 5, 6 and 7° at 3 m s^{-1}, similar responses to what was observed for the younger skiers of this study. This suggests that the observed crossover point of advantage/disadvantage between V2 and V1 skating probably applies even with elite senior skiers.

Part 2

Physiological responses for varying speeds

The second part of this study involved a skating technique comparison on a fixed slope of 5° and with increasing speed. The 5° slope was close to the crossover points which were observable from the results of Part 1. A similar examination on fixed slopes was reported by Hoffmann et al. (1994) comparing the classic techniques diagonal stride and double poling at 1.7 and 7.1% grade and increasing speed. A comparison of V1 and V2 in the present study showed a similar pattern of mean VO_2 responses for both V1 and V2. The oxygen uptake increased in an approximately linear manner with skiing speed similar to many other locomotion patterns (Åstrand and Rodahl 1986). Within the range of speeds from 2.25 m s^{-1} to 3.00 m s^{-1} which all subjects completed, V1 had a significantly lower oxygen uptake compared to V2 ($p < 0.01$). At 3.25 m s^{-1}, some subjects could not complete the stage, but for the 10 that did, mean RER values exceeded 1 indicating they were skiing at race pace or faster.

Similar to the VO_2 response, HR is reported to increase linearly with work rate in many types of exercise (Åstrand and Rodahl 1986). Findings from the present study confirmed this relationship for both V1 and V2 skating but the magnitudes were different. V1 skating had a significantly lower HR through the range of speeds compared to V2 ($p=0.002$). Previous studies have reported the HR obtained at racing speed and at maximal velocity not to vary between techniques (Bilodeau et al. 1991; Karvonen et al. 1987, 1989). In the present study, the velocities were not maximal since the duration of the sessions was 5 min, but we anticipate that race pace was reached at the higher speeds. It is well known that HR at a given oxygen uptake is higher when the exercise is performed with the arms than with the legs (Åstrand and Rodahl 1986), however, V1 and V2 skating involves both leg and arm exercise, but with different movement patterns. V1 technique has one "strong" side where a poling thrust goes together with the skating action, while on the "weak" side, only the skating leg gives propulsive force. V2 has one double pole thrust for each leg's skating stroke. This means that V1 has one pole plant per cycle where as V2 has two. Consequently at a given intensity, V2 technique often requires a higher working frequency with the arms compared to V1. This may affect HR and be one explanation for why the HR was observed to be higher with V2 skating technique.

Blood lactate concentration increased systematically as speed increased in both techniques. However, V1 skating had significantly lower La through the range of speeds compared to V2 with a difference of approximately 1 mM at each step of speed. For low angled uphills, the V2 technique can be effectively used without additional blood lactate accumulation compared to V1 skating, but on moderate to steeper uphills, V2 skating is likely to result in elevated La compared to V1 skating at the same speed.

Physiological responses related to mechanics

From the present findings, we may raise the question: Why are the relative economies for V1 and V2 dependent upon grade? One explanation may involve the proportion of the skating reaction forces aimed in the direction of movement, which will influence the energy cost of a locomotion technique. Ski reaction forces in skating skis are oriented approximately perpendicular to the ski surface. The ski is set down at an angle to the forward direction and placed with a ski edging angle. When a skier pushes through the ski to the snow, a reaction force is generated with both horizontal and vertical components. When the ski is angled with respect to the forward direction, the horizontal reaction force can be propulsive (Smith 2003). The effectiveness of the skating stroke to drive the skier forward will change in proportion to the propulsive component of force. Thus, ski and pole orientation can influence the effectiveness of reaction forces generated by the skier. On flat terrain, only air and snow drag forces resist the motion of the skier, while on uphill terrain, the skier also has to work against gravity force. Consequently, on flat terrain, the skis are less angled away from the forward direction requiring relatively modest propulsive forces to maintain skiing speed. In uphill skiing, the ski angles increase considerably as this condition requires greater propulsive force to maintain uphill speed. V1 skating is used over a wide range of terrain because the technique makes it possible to adjust ski angles from rather narrow to quite wide. The skier then generates propulsive force components during smooth pushes from one ski onto the other with a complete weight shift. In contrast, V2 skating has shorter poling action compared to V1, which requires greater accelerations of the arms with each poling motion. This may also affect the trunk motion where there is little time for trunk flexion. In addition, the ski angles in V2 are typically quite small, thus, the propulsive forces generated during each skating stroke cannot be as large as when the skis are angled more widely which is typical of V1 skating.

More than half of a skier's propulsive forces are generated through the poles during uphill ski skating using V1 technique on slopes and speeds comparable to those of the current study (Smith 1989). This may point toward upper body work having a substantial influence on the work economy under these conditions. Millet et al. (1998b) examined poling forces for different skating techniques across a range of speeds on a slight grade. The results indicated a greater use of the upper body with V2 technique compared to V1. These preliminary data are interesting in relation to the present study, and can help explain the difference in work economy between V1 and V2 skating. On low angled slopes, both V1 and V2 techniques may allow a similar distribution of workload between legs and upper body. However, as the slope increases, ski orientation angles are more easily widened for the V1 technique than for V2 which involves poling along with both skating strokes. The wider ski placement of V1 allows a greater propulsive force component from each skating stroke than in V2 skating. This reduces the workload required of the upper body to maintain a skiing speed. In contrast to this, with V2 skating a larger proportion of propulsive force must be generated through upper body work which also comes at higher frequencies of poling due to two poling actions per cycle. The work distribution between upper and lower body may affect VO_2 and lactate production due to differences of muscle mass and working conditions. These in turn may affect muscular efficiency which is inversely related to work intensity (Gaesser and Brooks 1975; Powers et al. 1984). Future testing of the relative proportions of upper and lower body contributions to propulsive force in V1 and V2 skating for various slopes will clarify whether these conjectures correctly explain the comparative costs of the two techniques.

In summary, V1 and V2 skating techniques are often used by ski racers on similar, moderate uphill terrain.

Comparisons of oxygen uptake, HR, La, and perceived exertion for the two techniques at the same speed suggest that V2 skating *may* be disadvantageous on slopes steeper than about 4–5° for treadmill roller ski skating. Skiing on snow will likely involve greater drag forces (air and snow) acting against a skier, hence, corresponding conditions on snow may involve rather modest slopes of 3 or 4°. The trends of the present data suggest that V2 technique *may* be advantageous on low angle terrain with perhaps lower VO_2, HR, and La, but those flat to modest uphill slopes will require additional confirmation for this idea. Applying the results of this study to help optimize skier performance, coaches and skiers should refrain from thinking that V2 is simply faster than V1 skating whenever it can be accomplished. On moderate to steep uphill terrain, V2 skating may involve greater cost than V1 and have physiological consequences which could negatively influence overall race performance.

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