Paced Breathing in Roller-Ski Skating: Effects on Metabolic Rate and Poling Forces

Nicolas Fabre, Stéphane Perrey, Loïc Arbez, and Jean-Denis Rouillon

Purpose: This study aimed (1) to determine whether paced breathing (synchronization of the expiration phase with poling time) would reduce the metabolic rate and dictate a lower rate of perceived exertion (RPE) than does spontaneous breathing and (2) to analyze the effects of paced breathing on poling forces and stride-mechanics organization during roller-ski skating exercises. Methods: Thirteen well-trained cross-country skiers performed 8 submaximal roller-skiing exercises on a motorized driven treadmill with 4 modes of skiing (2 skating techniques, V2 and V2A, at 2 exercise intensities) by using 2 patterns of breathing (unconscious vs conscious). Poling forces and stride-mechanics organization were measured with a transducer mounted in ski poles. Oxygen uptake (VO₂) was continuously collected. After each bout of exercise RPE was assessed by the subject. Results: No difference was observed for VO₂ between spontaneous and paced breathing conditions, although RPE was lower with paced breathing (P < .05). Upper-limb cycle time and recovery time were significantly (P < .05) increased by paced breathing during V2A regardless of the exercise intensity, but no changes for poling time were observed. A slight trend of increased peak force with paced breathing was observed (P = .055). Conclusion: The lack of a marked effect of paced breathing on VO₂ and some biomechanical variables could be explained by the extensive experience of our subjects in cross-country skiing.

Key Words: cross-country skiing, oxygen uptake, perceived exertion, poling efficiency

Interactions between locomotion and ventilation have been observed and described for varying modes of locomotion in humans, including running or walking, cycling, rowing, hand-rim wheelchair propulsion, and cross-country skiing. The observation that many activities exhibit coordination of respiratory and

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locomotor cycles would seem to imply that there is some advantage to coordination. The theoretical advantages of breathing entrainment (ie, locomotion that drives ventilation) during dynamic exercise are a possible enhancement in efficiency of the stride mechanics and a decrease of both the energy cost and the rating of perceived exertion (RPE). With regard to this idea, Macleman et al found no effect of paced breathing in either rowing economy or RPE in trained subjects. Nonetheless, a slight but significant reduction in metabolic rate (ie, VO2) has been observed under a paced-breathing mode during submaximal cycling and running exercises, in which a tight coordination (eg, a 1:1 frequency coupling) between locomotor and breathing rhythms was observed.

During arm propulsion in cross-country skiing, primary locomotor and accessory respiratory muscles are in part the same (ie, the muscles of the abdominal wall, the intercostals, the sternocleidomastoids, and the pectoral muscles). Therefore, it could be hypothesized that by consciously synchronizing expiration phase with poling time and inspiration phase with upper-limb recovery time (1:1 ratio frequency locking exercise), the respiratory workload and, thus, the metabolic rate of cross-country skiing would be reduced as a result of tight coordination between breathing and arm-propulsion cycles. One advantage of breathing in a coupled pattern is that it might minimize potential conflict between locomotor and respiratory events so that the muscles that affect both ventilation and locomotion can operate economically. In the same way, Bramble and Jenkins demonstrated that in trotting dogs, the thoracoabdominal displacements associated with foot strike assisted ventilatory flow to a large extent. If so, the hypothesis that the work of breathing is decreased by reducing the mechanical interference between locomotion and breathing appears reasonable, especially for cases in which the locomotor and breathing rhythms show 1:1 coordination. Because of the paucity of such data in the literature, the influence of a paced breathing pattern (conscious entrainment) in cross-country skiing, which uses several skating techniques with various timing of arm-propulsion movements on the cardiorespiratory and the perceptual responses, deserves specific attention, especially for competitive cross-country skiers.

On the other hand, the consequences with and without conscious entrainment of the breathing rhythm on some biomechanical variables (force and stride timing) had never been investigated regardless the mode of locomotion. For competitive cross-country skiers, such results could provide useful information on which stride-mechanics organization and breathing patterns to adopt to attain better poling efficiency. Recently, Holmberg et al showed that a smaller minimum hip angle was a discriminatory factor in the performance of the cross-country skiers during double-poling exercises. A marked synchronization between expiration phase and poling time can facilitate important trunk flexion and, thus, might enhance poling efficiency. Consequently, we hypothesized that paced breathing with a synchronization of the expiration phase with poling time could result in an increase in poling efficiency in cross-country skiing.

The present study aimed to (1) determine whether paced breathing would reduce the metabolic rate and dictate a lower RPE than spontaneous breathing and (2) analyze the effects of paced breathing on poling forces and stride-mechanics organization during roller-ski skating exercises.
Methods

Subjects
Thirteen well-trained cross-country skiers (11 men and 2 women, regional to national class, age 22 ± 3 years, height 177 ± 10 cm, and body weight 67 ± 8 kg) volunteered to participate in this study. Participants were asked to refrain from ingesting caffeine or alcohol for at least 12 hours before testing. They were asked to eat a light meal 2 hours before testing. All participants were blind to the purpose of the study. The study protocol complied with the Helsinki declaration for human experimentation and was approved by the local ethics committee for human research. Possible risks and benefits were explained, and written informed consent was obtained from each subject before their participation.

Determination of Working Intensities
During the first visit to the laboratory, each subject underwent an incremental roller-ski test to volitional exhaustion on a motorized treadmill (belt dimensions 1.8 × 3 m, Training Treadmill S1830, HEF Techmachine, Andrézieux-Bouthéon, France). The belt consists of a nonslip surface that allows the use of roller-ski-pole carbide tips. At the beginning of each test the skier was secured by a safety harness suspended from the ceiling. Before testing, each skier was fully familiarized with roller-skiing on a treadmill.

The continuous incremental test involved roller-skiing at a constant speed (7.5 km/h for the women and 8.5 km/h for the men) during the first four 3-minute stages and with a treadmill slope increasing from 4% to 10% each 2%; thereafter, speed increased by 1 km/h but slope remained at 10%. This kind of protocol, routinely used by competitive cross-country skiers, is similar to that proposed by Rundell.17 During the incremental test, all skiers used the V2-alternative skate technique or V2A (corresponding to a symmetrical double-pole plant as body weight is transferred to 1 ski) during the first stages of the test, then the V1 skate technique (similar to V2A except than the pole plant is asymmetrical and slightly asynchronous18) during the final stages, when the treadmill slope became steeper. These techniques are described fully elsewhere.19

From this incremental test, maximal oxygen uptake (VO\textsubscript{2max}) and 2 submaximal intensities corresponding to the first (I\textsubscript{1}) and the second (I\textsubscript{2}) ventilatory thresholds were determined. To be certain that subjects reached their VO\textsubscript{2max}, the following criteria were used: a respiratory-exchange ratio above 1.1, a measured maximal heart rate higher than 95% of theoretical maximal heart rate (220 – age), and an inability to maintain treadmill pace. Three reviewers blinded to the experiment determined I\textsubscript{1} and I\textsubscript{2} individually by visual analysis of the breakpoints of the minute ventilation (V\textsubscript{E}) and the ventilatory equivalents of carbon dioxide (V\textsubscript{E}/VCO\textsubscript{2}) and oxygen (V\textsubscript{E}/VO\textsubscript{2}) over time.20

Experimental Protocol
All subjects were familiar with all skating techniques and routinely used them during practice while roller-skiing or skiing on snow. The same roller skis (Elpex F1, Swedski, Sweden) were used by all subjects and for all tests. On 2 separate
days, 8 submaximal roller-ski skating exercises were performed for 6 minutes each on a ski treadmill at speeds and grades corresponding to subjects’ individual I1 (8.3 ± 0.1 km/h and 4.0% ± 0.0%, respectively) and I2 (8.2 ± 0.2 km/h and 7.7% ± 0.2%, respectively) intensities. The following testing conditions were carried out in a random order:

- V2A skate technique with spontaneous breathing at a low intensity: V2AI1
- V2A skate technique with spontaneous breathing at a high intensity: V2AI2
- V2 skate technique (ie, a symmetrical double pole plant during body-weight transfer to each ski) with spontaneous breathing at a low intensity: V2I1
- V2 skate technique with spontaneous breathing at a high intensity: V2I2

Each of these 4 tests was repeated with the subjects consciously synchronizing expiration phase with poling time and inspiration phase with upper-limb recovery time (ie, by using a 1:1 ratio): V2AI1p, V2AI2p, V2I1p, V2I2p (p for paced breathing). Subjects were instructed to synchronize breathing pattern (expiration and inspiration phases) with upper body movements before each skiing bout. We coached them during skiing bouts if needed.

Each exercise was followed by a recovery period of at least 10 minutes to keep subjects’ breathlessness, hyperventilation, and afferent metabolic stimuli at a minimum. We ensured that subjects recovered fully before they performed another skiing bout. Immediately after each bout of roller-skiing, a global rating of perceived exertion (RPEg) and a rating of perceived exertion based on breathlessness sensations (RPEb) using the Borg 6-to-20 scale21 were requested.

**Mechanical Measurements**

Modified aluminum ski poles (Rollerlite, Swix, Lillehammer, Norway) with a single-axial force transducer (model 208B03, PCB Piezotronics, Inc, Depew, NY) mounted 1 cm below the handles were used to collect pole-force data (Figure 1). The force transducer was regularly calibrated throughout the experimental period by applying a full range of axial loads from –50 N to 350 N to the transducer. Only data from the right ski pole were analyzed. Data were recorded for 15 seconds at a sampling frequency of 100 Hz. Similarly modified ski poles were previously used by Millet et al.18,22-24

**Physiological Measurements**

Values of $V_{\text{t}}$, breathing frequency (Rf), tidal volume ($V_{\text{t}}$), end-tidal partial pressure ($P_{\text{ET}}$,CO$_2$), and VO$_2$ were continuously determined breath by breath during all tests (Cosmed K4b$^2$, Rome, Italy). Gas analyzers were calibrated before each test with ambient air (O$_2$ 20.93% and CO$_2$ 0.03%) and a gas mixture of known composition (O$_2$ 16.00% and CO$_2$ 5.00%). An O$_2$ analyzer with a polarographic electrode and a CO$_2$ analyzer with an infrared electrode sampled expired gases at the mouth. The face mask, which had a low dead space (70 mL), was equipped with a low-resistance, bidirectional digital turbine (28-mm diameter). This turbine was calibrated before each test with a 3-L syringe (Hans Rudolph Inc, Dallas, Tex). Face masks allowed subjects to simultaneously breathe with the mouth and nose for more comfort. It has been demonstrated that the use of a mouthpiece and nose
clip can affect $V_T$, inspiratory flow, and $Rf$. Heart rate (HR) was continuously measured with a wireless Polar monitoring system (Polar Electro Oy, Kempele, Finland) and synchronized with the Cosmed system; consequently, mean HR within each breath was calculated.

Data Analysis

All respiratory values were analyzed during metabolic steady state, that is, after the first 2 minutes of each submaximal constant-load exercise.

The force data of the right pole were smoothed by a 3-point moving time average. Then, 4 timing variables (in seconds) were determined (Figure 1): cycle time (CT), poling time (PT), upper-limb recovery time (RT = CT – PT), and peak poling force (PF) expressed as a percentage of body weight.

Statistical Analysis

A 2-way repeated-measures ANOVA (breathing patterns [2] × modes of roller-skiing exercises [4]) was used. If statistical significance was found, a Tukey post hoc test was conducted to identify where those differences occurred. For all statistical comparisons, the level of significance was set at $P \leq .05$. Values presented are expressed as mean ± SD.

Results

All the subjects were pooled in the statistical analysis because results were identical whether or not the women were included in the data set. Speed and grade values
during incremental and submaximal roller-skiing tests are given in Table 1. The mean value of VO₂ was 65.2 ± 8.5 mL·min⁻¹·kg⁻¹.

**Metabolic, Cardiorespiratory, and Perceptual Data**

Physiological and perceptual variables during submaximal exercises are summarized in Table 2. During the submaximal exercises, I₁ and I₂ intensities corresponded to 65.7% ± 3.0% and 83.3% ± 5.6%, respectively, of VO₂max.

The 2-way repeated-measures ANOVA revealed that V̇̇⁻ was higher with paced breathing than with spontaneous breathing (P ≤ .05). The Tukey post hoc test indicated that the difference was present for the V₂I₁ mode of roller-skiing exercise (P ≤ .001). This increase was caused by an increase in Rf with paced breathing (P < .01) concomitant with a decrease in V̇⁻ (P < .01). Paced breathing resulted in a significant reduction of end-tidal PCO₂ compared with the spontaneous-breathing condition (PETCO₂ = 37.0 vs 38.5 mmHg, respectively, P ≤ .05). The post hoc tests showed that this significant reduction was present for the V₂A₁ and the V₂I₁ modes of roller-skiing exercises (P ≤ .05). No significant difference was observed in VO₂ between spontaneous and paced breathing. RPEg was significantly lower with paced breathing, however, than with spontaneous breathing (P ≤ .001). In fact, the post hoc tests indicated that RPEg for both V₂A₁ and V₂I₂ was significantly lower with paced breathing (P < .05 and P < .01, respectively).

**Poling Forces and Timing Data**

Results for RT, PT, CT, and PF are shown in Figure 2. CT and RT were significantly increased by paced breathing compared with spontaneous breathing during V₂A bouts (P < .05) but not during V₂ bouts regardless the exercise intensity. PT remained unchanged by paced breathing. PF tended to increase with paced breathing, but results did not reach statistical significance (P = .055).

Finally, the post hoc tests showed that CT, RT, and PT were longer with V₂A₁ and V₂A₂ compared with V₂I₁ and V₂I₂ (P < .01), and PF was higher with V₂I₂ than with V₂I₁ (P < .05).

**Table 1 Speed and Grade Values (Mean ± SD, N = 13) During Submaximal and Incremental Roller-Ski Skating Exercises**

<table>
<thead>
<tr>
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<th>Speed (km/h)</th>
<th>Grade (%)</th>
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<tbody>
<tr>
<td>I₁</td>
<td>8.3 ± 0.4</td>
<td>4.0 ± 0.0</td>
</tr>
<tr>
<td>I₂</td>
<td>8.2 ± 0.6</td>
<td>7.7 ± 0.6</td>
</tr>
<tr>
<td>Max</td>
<td>9.4 ± 0.9</td>
<td>10†</td>
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*I₁ indicates intensity 1, corresponding to the first ventilatory threshold; I₂, intensity 2, corresponding to the second ventilatory threshold; Max, maximal values obtained during the incremental roller-skiing test conducted to volitional exhaustion.

†Grade on the treadmill was imposed for all subjects (see Methods section).
Table 2  Relevant Physiological and Perceptual Variables During Submaximal Roller-Ski Skating Exercises, Mean ± SD, N = 13*

<table>
<thead>
<tr>
<th></th>
<th>Spontaneous Breathing</th>
<th>Paced Breathing</th>
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<tbody>
<tr>
<td></td>
<td>V2AI1</td>
<td>V2AI2</td>
</tr>
<tr>
<td>VO₂ (mL · min⁻¹ · kg⁻¹)</td>
<td>42.6 ± 5.5</td>
<td>49.9 ± 4.4</td>
</tr>
<tr>
<td>VE (L/min)</td>
<td>73.7 ± 10.9</td>
<td>102.6 ± 19.7</td>
</tr>
<tr>
<td>PₚETCO₂ (mmHg)</td>
<td>41.3 ± 2.5†</td>
<td>37.7 ± 2.0</td>
</tr>
<tr>
<td>RF (breaths/min)</td>
<td>35.4 ± 4.8</td>
<td>41.8 ± 4.9</td>
</tr>
<tr>
<td>VT (L)</td>
<td>2.1 ± 0.3</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>HR (beats/min)</td>
<td>150 ± 17†</td>
<td>173 ± 8</td>
</tr>
<tr>
<td>RPE₇</td>
<td>12.1 ± 1.6†</td>
<td>15.2 ± 1.7</td>
</tr>
<tr>
<td>RPE₉</td>
<td>11.1 ± 1.2</td>
<td>14.5 ± 2.1</td>
</tr>
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*VO₂ indicates oxygen uptake; VE, minute ventilation; PₚETCO₂, end-tidal partial pressure of CO₂; RF, breathing frequency; VT, tidal volume; HR, heart rate; RPE₇, global rating of perceived exertion; and RPE₉, rating of perceived exertion based on breathlessness sensation.

†Significant differences between spontaneous and paced breathing (P < .05).
Discussion

The first aim of this study was to investigate the hypothesis that conscious entrainment of breathing rhythm (paced-breathing condition) in cross-country skiing would reduce the metabolic rate and result in a lower RPE than with no conscious entrainment (spontaneous-breathing condition). Entrained breathing during exercise has been assumed to result from synchronization between the respiratory and locomotive muscles. This pattern of response might increase the efficiency of the mechanical work between breathing and locomotive activities, leading in turn to a decrease in total metabolic rate.\(^4\)\(^-\)\(^6\) Contrary to what we expected, however, we observed no reduction in VO\(_2\) in any roller-ski-skating bouts under a paced-breathing mode (Table 2). This finding is in agreement with those described in previous studies involving cycling\(^2\)\(^7\) and rowing.\(^8\) The rowing study, also involving upper-limb propulsion, indicated that the benefit of a tight coupling between locomotion and ventilation on metabolic rate might require months to years of training. In the present study, our subjects were highly trained and well experienced in roller-ski skating. Based on this and on the minimal difference observed in breathing-pattern responses (Rf and V\(_t\)) between paced- and spontaneous-breathing modes.

Figure 2 — (A) Recovery time, (B) poling time, (C) cycle time, and (D) peak force during roller-ski skating exercises, mean ± SD. *Significant differences between spontaneous and paced breathing (\(P < .05\)).
(Table 2), we can therefore hypothesize that our subjects had already and naturally developed a tight coordination between breathing and locomotor rhythms (unconscious entrainment) over their years of training (more than 15 years in average). Therefore, it might have been too difficult to further increase their synchronization of the expiration phase with poling time under a paced-breathing mode to observe any significant influence on metabolic rate. Further study with less-experienced skiers is required to clarify this point.

In addition, the flexibility of breathing-pattern responses of experienced Nordic skiers in reaction to different metabolic demands during arm exercise (4 modes tested in the present study) is probably reduced because of a consistent phase coupling of respiration to locomotion. It is interesting that the breathing-pattern responses during combined-arm exercise modes (bilateral synchronous and asynchronous arm poling) have been shown to be distinct from those during leg exercise, suggesting that skiers might also not synchronize their breathing well to poling rate. Furthermore, Takano and Deguchi argued that the influence of entrainment of the breathing rhythm depended on the difference between conscious and unconscious entrainment during rhythmic exercise. Compared with the spontaneous-breathing condition, a higher $V_{e}$ observed in the present study only for V2 skiing technique at the lowest exercise intensity might result from a greater ventilation:perfusion ratio in the lungs, leading to a lower $P_{et}CO_{2}$ during submaximal exercise. Familiarity with the exercise mode might also be related to the difference in $P_{et}CO_{2}$ responses (Table 2). Whether the cyclical ventilatory pattern resulting from the fixed entrainment of breathing proposed in the present study presents a benefit or a constraint to the overall ventilatory response to exercise might be very difficult to assess quantitatively, especially in humans. It seems quite possible, if not likely, that locomotion-induced enhanced flows could make a significant contribution to the phenomenon of exercise hyperventilation, as indirectly indicated by lowered $P_{et}CO_{2}$.

In the present study, and in accordance with our initial hypothesis, perceptual data (Table 2) show that the subjects felt more comfortable during roller-ski skating exercises with paced breathing, a phenomenon already reported previously in runners. Because locomotor and respiratory muscles are in part involved simultaneously during cross-country roller-skiing (poling movement), paced breathing could lead to reduced strain on the respiratory muscles at higher exercise intensity. This is in full agreement with the result of a decrease in RPE values when respiratory muscles were unloading during a bicycle time to exhaustion. If perceptual data can be lowered under a paced-breathing mode as in the present study, we suggest that a training period and adaptive strategies of the breathing pattern as a function of the locomotor rhythm could permit a very tight coordination and, consequently, could reduce the metabolic rate of locomotion in cross-country skiers.

The second aim of the present study was to analyze the effects of paced breathing on poling forces and stride parameters during roller-ski skating. To our knowledge, such a biomechanical analysis in relation to breathing pattern has never been investigated. As expected, we noted first an important difference in stride-mechanics timing between V2A and V2 skating techniques in roller-skiing. Values of CT, RT, and PT were significantly longer in V2A than in V2 exercises, regardless of exercise intensity. Second, CT and RT were significantly
increased with V2A12 and V2I2 compared with V2A11 and V2I1. Overall, these observations confirmed previous results of Millet et al. The main interest in performing the biomechanical analysis of arm movements was to verify the hypothesis of enhanced poling efficiency (based on stride mechanics of the upper limbs) under a paced-breathing mode. For experienced runners, it has been suggested that tight coupling of breathing to locomotion might improve muscle force in the lower limbs. In cross-country skiing, paced breathing could allow a larger trunk flexion, a parameter identified recently as a discriminate factor in global skiing performance. A larger trunk flexion during poling motion involves a more effective orientation of poling forces and thus increases the propulsive forces. Therefore, a larger trunk flexion would be responsible in part for improved poling efficiency. According to Millet et al., increased poling time would be indicative of greater trunk flexion during the poling motion.

In the present study, the poling time was not significantly increased by a paced-breathing mode under any of the conditions imposed (2 skating techniques and 2 exercise intensities). PF tended to increase with paced breathing, however, although significance was not achieved ($P = .055$). Moreover, the paced breathing induced a significant increase in CT with the V2A12 and V2A11 modes of roller-skiing. Thus, paced breathing reduces the poling cycle rate with an increase in PF. In the same way, it has been demonstrated during cycling that increased force on the pedals was associated with a decrease in cycle rate. The trend for a higher PF could confirm a slight improvement in poling efficiency with paced breathing, as expected. Again, it would be necessary to test less-experienced cross-country skiers to confirm the slight trend of increasing peak poling forces under a paced-breathing mode.

Conclusion

In conclusion, this study demonstrated that paced breathing had no significant effect on metabolic rate in experienced cross-country roller skiers. Nonetheless, this mode of breathing decreased the rating of perceived exertion. Analysis of poling forces and stride-mechanics timing showed that there were no changes during the various proposed roller-skiing exercise tests; a slight trend of increased peak poling forces with the paced-breathing condition was observed, however. We explain the lack of a marked effect of a paced breathing in roller-ski skating on metabolic rate and biomechanical variables when compared with spontaneous breathing by the subjects’ extensive experience in cross-country roller-skiing. In light of the minimal difference in breathing rates between paced and spontaneous breathing, we hypothesized that the subjects had unconsciously already developed a tight coordination between breathing and locomotor rhythms during their years of practice.

Acknowledgments

We are indebted to Dr Martin D. Hoffman, who nicely lent the modified aluminum ski poles. The authors also acknowledge the assistance of all those who took part in this study, as well as Dr Alain Groslambert and Catherine Capitain for their contribution.
References


