The effects of prior high intensity double poling on subsequent diagonal stride skiing characteristics

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Abstract

Purpose: To investigate the influence of prior high intensity double poling (DP) on physiological and biomechanical responses during subsequent diagonal stride (DIA).

Methods: Eight well-trained male cross-country skiers (age 22 ± 3 yr; VO2max 69 ± 3 ml · kg⁻¹ · min⁻¹) roller-skied on a treadmill sequentially for 3 min at 90% DIA VO2max (DIA1), 3 min at 90% DP VO2peak and 3 min at 90% DIA VO2max (DIA2). Cardio-respiratory responses were monitored continuously and gases and metabolites in blood from the a. femoralis, v. femoralis and v. subclavia determined. Pole and plantar forces and EMG from 6 lower- and upper-body muscles were measured.

Results: VO2 decreased from DIA1 to DP and increased again to DIA2 (both P < 0.05), with no difference between the DIA sessions. Blood lactate rose from DIA1 to DP to DIA2. O2 extraction was attenuated during DP (P < 0.05), but was the same during DIA1 and DIA2. EMG_RMS for arm muscles during poling phase, as well as peak pole force and cycle rate were higher, while leg muscle activity was lower during DP than both sessions of DIA (all P < 0.05). The ratio of upper-/whole-body EMG_RMS correlated negatively with O2 extraction in the arms during both sessions of DIA (P < 0.05).

Conclusions: In well-trained skiers skiing at high-intensity DP prior to DIA did not influence VO2, muscle activation or forces in the latter. At race intensity DP does not influence the distribution of work between upper- and lower-body muscles were measured.

Keywords: EMG; Force; Oxygen extraction; Oxygen uptake

Background

Of the several different sub-techniques involved in classical cross-country skiing, diagonal stride (DIA) and double poling (DP) have been most frequently studied. With DIA, the skier utilizes both the arms and legs in a diagonal fashion for propulsion and this is considered to be whole-body exercise (Lindinger et al. 2009). In the case of DP, most propulsive force is supplied by the upper-body, although a dynamic leg movement also contributes to the application of body weight to pole forces (Holmberg et al. 2006; Rud et al. 2014). Consequently, in connection with both of these sub-techniques, and particularly DP, recovery of the upper-body muscles between strokes might be limited.

With regards to cardiovascular regulation, with a similar absolute pulmonary oxygen uptake (VO2), delivery of O2 to the arms and VO2 are higher, but extraction of O2 by the arms lower with DP than DIA (Calbet et al. 2005). In the case of DIA, when exercise intensity is reduced from high to moderate, O2 extraction in the arms is lowered to a greater extent than in the legs, probably due to a more pronounced decrease in the activation of arm muscles (Björklund et al. 2010). With DP the opposite is observed, i.e., O2 extraction in the arms is reduced to a lesser extent than in the legs as the intensity of exercise is diminished, apparently because strong activation of the muscles of the upper-body is maintained (Stöggl et al. 2013).

Furthermore, the skeletal muscles of the arms and legs differ with respect to the production and oxidation of lactate, with the arms producing more at a given workload (Ahlborg and Jensen-Urstad 1991). Thus, more extensive upper-body activation during DP compared to DIA should lead to a higher systemic concentration of lactate with the former sub-technique, as has, indeed,
been shown by Van Hall et al. (2003) to be the case with exercise of moderate intensity (~76% VO2max). In that investigation and the study by Calbet et al. (2005), the cardiovascular and metabolic influence of DP on subsequent DIA were analyzed to a certain extent, but no direct comparisons between DIA before and after DP were made. Moreover, analysis of higher exercise intensities (race intensity) is also important, since the distinctly higher muscle activation and application of force involved might cause mechanical hindrance of O2 extraction and thereby elevate blood levels of lactate (Stöggl et al. 2013).

Whereas DIA and DP have both been characterized individually from a physiological and biomechanical perspective during simulated races (Larsson and Henriksson-Larsen 2005; Mogløni et al. 2001; Mygind et al. 1994; Ortenblad et al. 2011; Wele et al. 2003), the influence of these sub-techniques on one another remains to be examined. Previous investigations on different modes of exercises involving the legs have revealed that the biomechanical and physiological characteristics of running are influenced negatively by prior cycling in the case of moderately trained, but not elite triathletes (Bonacci et al. 2010, 2011). In addition, after this transition, only the latter preserve their running economy, with no change in VO2. With repeated sprints of cross-country skiing the fatigue experienced by the upper-body muscles already during the first sprint leads to a shift in body position and, consequently, less effective application of force during DP (Zory et al. 2009, 2011).

Accordingly, the upper-body muscle fatigue induced by high-intensity DP might alter the relative activation of arm and leg muscles, together with pole and plantar forces, during subsequent high-intensity DIA. Thus, our aim here was to examine the influence of DP on subsequent DIA at a simulated race intensity of ~90% of VO2max/peak from a biomechanical and physiological perspective. The hypothesis was that DP alters the distribution of work between the upper- and lower-body, i.e., decreases pole force and activation of arm muscles during subsequent DIA, thereby reducing the O2 extraction by the arms.

Methods

Subjects

The 8 well-trained male cross-country skiers who volunteered (Table 1) were informed about the test procedures and possible risks prior to providing their written consent to participate. The research techniques and experimental protocol were pre-approved by the Regional Ethical Review Board in Umeå, Sweden (#08-049M) and performed in accordance with the Declaration of Helsinki.

The general experimental protocol

All tests were performed on a motor-driven treadmill (Rodby RL 3000, Vänge, Sweden) and, to minimize variations in rolling resistance, using the same pair of roller skis (Pro-Ski C2, Sterners, Nyhammar, Sweden). All of the participants were well accustomed to treadmill roller skiing, both as part of their regular training and from their involvement in previous testing. They visited the laboratory on two occasions: a) first, to carry out a preliminary test to determine VO2max, maximal heart rate (HRmax) and the linearity of the velocity-VO2 relationship for DIA and DP; and b) two days later to perform a continuous experimental protocol involving DIA and DP at race intensity.

The preliminary test

The velocity required to obtain 90% VO2max with DIA and 90% peak oxygen uptake (VO2peak) with DP were established employing separate linear graded protocols. In the case of DIA, VO2 was determined at several submaximal workloads separated by a one-minute break at a fixed inclination of 6.5°, with an initial velocity set to 6 km·h⁻¹. The increase for the submaximal workloads was 2 km·h⁻¹ using four minute long bouts. During this submaximal protocol capillary blood samples were taken between workloads for determination of lactate and the onset of blood lactate accumulation (OBLA) (4.0 mmol·l⁻¹) (Ivy et al. 1980; Sjödin and Jacobs 1981). VO2max values were established using a ramp protocol starting at 11 km·h⁻¹ at an incline of 4°, with an increase in gradient by 1° every minute. One day later the VO2peak for DP was obtained starting at a fixed inclination of 1°, initial velocity of 17 km·h⁻¹, and a 2 km·h⁻¹ increase in workload every fourth minute, until exhaustion. Using the means of the three highest consecutive VO2 values during the last

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### Table 1 Anthropometric and physiological characteristics of the 8 well-trained male cross-country skiers who participated

| Variable          | Mean ± SD |
|-------------------|-----------|
| Age (yr)          | 22 ± 3    |
| Height (cm)       | 183 ± 4   |
| Weight (kg)       | 79 ± 6    |
| BMI               | 23.6 ± 2.1|
| VO2max (l·min⁻¹) | 5.4 ± 0.3 |
| VO2max (ml·kg⁻¹·min⁻¹) | 69 ± 3 |
| VO2peak (l·min⁻¹) | 4.8 ± 0.4 |
| VO2peak (ml·kg⁻¹·min⁻¹) | 62 ± 3 |
| OBLA (%VO2max)   | 82 ± 4    |
| LT (%VO2max)     | 76 ± 3    |
| LT (l·min⁻¹)     | 4.1 ± 0.4 |
| HRmax (beats·min⁻¹) | 189 ± 5 |

VO2max, Maximal O2 uptake; OBLA, onset of blood lactate accumulation (4 mmol·l⁻¹); LT, Lactate threshold; HRmax, Maximal heart rate.
minute at each submaximal workload, with a total sampling time of 30 s (mixing chamber), simple linear regression was applied to calculate the velocities required to achieve the targets of 90% VO_{2max} (DIA_{LIN}) and 90% VO_{2peak} (DP_{LIN}).

**Experimental procedures**

The subjects reported to the laboratory two hours before starting the experimental protocol and were fitted with the EMG system and, thereafter, to normalize the amplitudes of the signals obtained, performed maximal voluntary contractions (MVC) with each muscle. Next, they rested in a supine position while the three catheters were inserted under local anesthesia (Carbocain 1%), utilizing an ultrasound system (Mindray DigiPrince DP-6600, Mindray Bio-Medical Electronics Co., Shenzhen, China) to visualize the vessels, as reported elsewhere (Calbet et al. 2005). For sampling arterial blood, a 16-gauge catheter (Arrow ES-04401, 300 mm, Arrow International Inc., Reading, PA) was inserted percutaneously using the Seldinger technique. Thereafter, a 20-gauge catheter (Arrow ES-04150, 120 mm) was inserted into the right femoral vein for collection of venous blood. Finally, another 16-gauge catheter (Arrow ES-04401, 300 mm) was inserted into an antecubital vein and then advanced into the subclavian vein for additional sampling of venous blood. (For further details, see Björklund et al. (2010)). All three catheters were sutured to the skin to minimize the risk of movement during exercise and connected to tubing (Alaris ES-04401, 300 mm, Arrow International, Munich, Germany). These systems for determination of the pole and plantar forces were validated and calibrated utilizing procedures described previously (Holmberg et al. 2005).

**Force measurements**

Each participant used custom-made carbon-fiber racing poles adjusted to his preferred length. The ground reaction force was measured by a strain gauge force transducer mounted directly below the grips of these poles (Hottinger–Baldwin Messtechnik GmbH, Darmstadt, Germany). Plantar ski reaction forces were recorded at 100 Hz by a Pedar mobile system (Novel GmbH, Munich, Germany). These systems for determination of the pole and plantar forces were validated and calibrated utilizing procedures described previously (Holmberg et al. 2005).

**EMG measurements**

The EMG activity at the surface of the triceps brachii, latissimus dorsi, rectus abdominis, gluteus maximus, and gastrocnemius (medial head) muscles on the right side of the body were recorded employing pre-gelled bipolar Ag/AgCl surface electrodes (Skin tact, Leonhard Lang GmbH, Innsbruck, Austria). Prior to fixation of these electrodes, the skin was shaved, abraded lightly, degreased, and disinfected with alcohol. The electrodes were positioned in parallel on the surface of the muscle belly in the direction of the fibers and 30 mm apart, in accordance with international standards (Hermens et al. 1999). The reference electrode was attached to the tibia. The active and reference electrodes for each muscle were connected to a single differential amplifier (base gain 500; input impedance >100 MΩ; common mode rejection ratio >100 dB; input range ±10 mV).

**Processing the EMG signals**

Prior to the calculation of EMG parameters, the raw signals were band-pass filtered digitally (10–400 Hz; Butterworth 2nd order) to remove both low- and high-frequency noise (Winter 1990). After full wave rectification of the signals the integrated and root mean square electromyography (IEMG and EMG_{RMS} respectively) values for defined phases of exercise were calculated for all of these muscles. After training several times, MVC was performed with each muscle (Acierno et al. 1995;
Holmberg et al. 2005). The recording and processing of MVC data were carried out according to Björklund et al. (2010). Statistical analysis (see further below) for IEMG and EMG<sub>RMS</sub> was performed using the sum, respectively the mean values for the arm (triceps brachii, and latissimus dorsi) and leg muscles (gastrocnemius, gluteus maximus, rectus femoris).

Collection and analysis of biomechanical data

EMG signals and pole forces were amplified with a telemetry recording system (TeleMyo 2400T G2, Noraxon, Scottsdale, AZ) and simultaneously stored (at a sampling rate of 3000 Hz) on a computer via an A/D converter card. Synchronization of the measurement of EMG signals and pole and plantar forces was achieved with a signal produced by the Pedar mobile system. The mean values for the ten successive cycles during the final 30 s of exercise at the three different bouts were subjected to statistical analysis.

Within each cycle of the DIA skiing, the following four phases were analyzed: 1–2) poling and recovery of the arms; 3) leg-gliding (starting from placement of the roller ski and ending when the leg force was minimal immediately prior to the increase in force associated with the push-off); and 4) the push-off and recovery of the legs. One such cycle was defined as extending from a pole plant to the next pole plant on the same side of the body. A cycle of DP skiing was divided into the poling and recovery phases. The average pole and plantar forces were calculated by dividing the integrated signal by the cycle time. All data were processed using the IKE-master software (IKE-Software Solutions, Salzburg, Austria).

Statistical analyses

All sets of data exhibited a Gaussian distribution, as confirmed by applying the Shapiro-Wilk test. Values are presented as means ± SD. A two way repeated-measures ANOVA (skiing technique × sampling site) was employed to test for differences between skiing techniques and sampling sites, as well as between biomechanical parameters associated with the upper- and lower-body. When a significant interaction was observed, paired sampled t-tests or a one-way ANOVA with repeated measures was performed. When only a single measurement at each workload was performed, a one-way ANOVA with repeated measures was used. A Bonferroni Post-Hoc test was performed on global effects identified by ANOVA. Pair-wise relationships between variables were compared using Pearson’s product moment correlation coefficient. A level of α < 0.05 was considered to be statistically significant in all cases. All statistical analyses were performed with the SPSS 18.0 program (IBM Corporation, Somers, NY).

Results

General observations

The calculated VO<sub>2</sub> for DIA and the averaged measured VO<sub>2</sub> during the first and second bout of DIA skiing were 4.84 ± 0.95, 4.89 ± 0.13 and VO<sub>2</sub> 4.99 ± 0.11 l·min<sup>-1</sup>, respectively (P = 0.081) (Figure 1). Similarly, the calculated VO<sub>2</sub> for DP and the averaged measured VO<sub>2</sub> during DP the skiing did not differ (4.35 ± 0.36 and 4.36 ± 0.49 l·min<sup>-1</sup>, respectively; P = 0.94). The cardiorespiratory and biomechanical values are documented in Table 2.

![Figure 1](https://example.com/vo2-chart.png)

**Figure 1** VO<sub>2</sub> values (means ± SD) during the three sessions of roller skiing on a treadmill. The mean calculated 90% VO<sub>2max</sub> (DIA<sub>LIN</sub>) and 90% VO<sub>2peak</sub> (DP<sub>LIN</sub>) are illustrated by the double line.
Table 2: Cardio-respiratory and biomechanical values for our 8 well-trained male cross-country skiers while roller-skiing with the diagonal stride (DIA) or double poling (DP) technique at 90% VO2max/peak on a treadmill

|                                | First session of DIA | DP       | Second session of DIA | F-value | P-value | Power |
|--------------------------------|----------------------|----------|------------------------|---------|---------|-------|
| **Cardio-respiratory parameters** |                      |          |                        |         |         |       |
| VO2 (l·min⁻¹)                   | 4.89 ± 0.36⁺         | 4.36 ± 0.49⁻ | 4.99 ± 0.11⁺          | F₁,₂₈,₆= 35.3 | P < 0.001 | 1.005 |
| Heart rate (beats·min⁻¹)        | 174 ± 4¹            | 168 ± 7¹ | 181 ± 4⁺              | F₀,₂₁= 14.7    | P < 0.001 | 0.994 |
| V̇E (l·min⁻¹)                   | 152 ± 8            | 155 ± 18 | 172 ± 14              | F₀,₂₁= 8.52     | P = 0.004 | 0.921 |
| O₂ pulse (ml per beat)          | 28.1 ± 2.4⁺         | 25.8 ± 3.1⁺ | 27.3 ± 2.2            | F₁,₁₇,₈= 5.77    | P = 0.041 | 0.581 |
| Breaths·min⁻¹                   | 47 ± 2⁺             | 52 ± 3⁺  | 53 ± 7                | F₀,₂₁= 6.79     | P = 0.027 | 0.672 |
| V̇O₂ (ml)                       | 3.24 ± 0.23⁺        | 2.97 ± 0.39⁻ | 3.23 ± 0.27⁺          | F₀,₂₁= 5.43     | P = 0.018 | 0.760 |
| Respiratory exchange ratio      | 1.07 ± 0.06         | 1.11 ± 0.06 | 1.09 ± 0.04           | F₀,₂₁= 1.74     | n.s.    |       |
| V̇E/V̇O₂                        | 31.2 ± 1.9⁺         | 35.6 ± 2.1⁺ | 34.9 ± 3.8⁺           | F₀,₂₁= 14.7     | P < 0.001 | 0.994 |
| V̇E/VO₂                         | 29.1 ± 1.1⁺         | 31.9 ± 1.4⁺ | 32.0 ± 2.7⁺           | F₀,₂₁= 10.7    | P = 0.002 | 0.966 |
| **Biomechanical parameters**    |                      |          |                        |         |         |       |
| Speed (km·h⁻¹)                  | 11.2 ± 0.3           | 243 ± 1.1 | 11.2 ± 0.3            | F₀,₂₁= 13.1     | P = 0.001 | 0.985 |
| Cycle rate (Hz)                 | 0.79 ± 0.02⁺        | 0.87 ± 0.02⁻ | 0.78 ± 0.01⁺          | F₀,₂₁= 4.91     | P = 0.028 | 0.693 |
| Cycle length (m)                | 3.94 ± 0.6⁺         | 7.82 ± 2.3⁺ | 4.00 ± 0.05⁺          | F₀,₂₁= 211     | P = 0.001 | 1.000 |
| Cycle time (s)                  | 1.28 ± 0.07⁺        | 1.16 ± 0.00⁻ | 1.30 ± 0.06⁺          | F₀,₂₁= 12.3     | P = 0.001 | 0.979 |
| Recovery time for the arms (s)  | 0.75 ± 0.06⁺        | 0.80 ± 0.06⁻ | 0.75 ± 0.05⁺          | F₀,₂₁= 4.91     | P = 0.028 | 0.693 |
| Relative arm recovery time (%)  | 58.7 ± 2.5⁺         | 68.9 ± 1.6⁺ | 57.9 ± 2.7⁺           | F₀,₂₁= 155     | P = 0.001 | 1.000 |
| Peak pole force (N)             | 101 ± 7.4⁺          | 287 ± 45.2⁺ | 96.0 ± 5.5⁺           | F₀,₂₁= 22.3     | P = 0.001 | 1.000 |
| Recovery time for the legs (s)  | 0.50 ± 0.04         | 0.52 ± 0.03 | n.s.                  | F₀,₂₁= 4.49     | P = 0.035 | 0.651 |
| Peak leg force (N)              | 666 ± 87            | 673 ± 80 | n.s.                  | F₀,₂₁= 9.47    | P = 0.003 | 0.937 |
| Impulse of pole force (Ns)      | 33.6 ± 5.9          | 39.4 ± 9.6 | 30.9 ± 3.7            | F₀,₂₁= 4.49     | P = 0.035 | 0.651 |
| Impulse of foot force (Ns)      | 481 ± 100           | 392 ± 54⁺  | 482 ± 79⁺             | F₀,₂₁= 9.47     | P = 0.003 | 0.937 |

The values are presented as means ± SD. VO2 oxygen uptake; V̇E minute ventilation; V̇O₂ tidal volume; Bonferroni correction was used to check for differences between time-points. A One-Way repeated ANOVA was used to compare the responses and a paired Student’s t-test was only when two time-points were compared.

*Statistically different from DIA,*

*Statistically different from DP,*

*Statistically different from DIA*.

Greenhouse-Geisser-adjusted ANOVA, since the sphericity was violated.

n.s. not statistically significant.

Muscle activation

During the poling phase the EMG_RMS for the arms was 36.7 and 49.7% higher with DP than during the first and second sessions of DIA skiing, respectively (both P < 0.05). Especially during DP, high EMG_RMS values of 99.7 ± 12.9 %MVC (range: 69–159 %MVC) were found. The relative EMG_RMS for the arms (whole body) for the entire cycle was 32.7% lower during DP (P < 0.001) than the first session of DIA (Table 3). The sums of the IEMG and average EMG (AEMG) for all of the muscles analyzed during both sessions of DIA were similar and greater than DP (IEMG: DIA₁: 207 ± 24; DP: 86 ± 26; DIA₂: 106 ± 25 %MVCs; AEMG: 93 ± 27, DP 72 ± 20, DIA₂ 79 ± 22 %MVC/s; P < 0.01 in both cases). The ratio of upper-/whole-body EMG_RMS was inversely correlated with arm O₂ extraction in the arms during both sessions of DIA (r = −0.918, P = 0.004 and r = −0.803, P = 0.03 respectively) (Figure 2A-B), whereas there was no such correlation in the case of DP.

Force and kinematics

Cycle rate and peak pole force were higher during DP than during both sessions of DIA (both P < 0.001), during which these values were similar. The impulse of pole forces was similar in all three sessions (P > 0.05). The absolute and relative (% cycle time) recovery times for the arms were longer with DP, with no difference between the two sessions of DIA (Table 2) (P > 0.05). During DIA, O₂ extraction in the legs was negatively correlated to minimal leg force during ground contact (the end of the gliding phase) (r = −0.821, P = 0.024) and to the IEMG and EMG_RMS for the entire cycle in the lower-body (r = −0.782, P = 0.038 and r = −0.794, P = 0.033, respectively). During DP, O₂ extraction in the legs was negatively correlated to minimal leg force (r = −0.941, P = 0.002) and positively associated with cycle length (r = 0.862, P = 0.013). O₂ extraction in the arms during DP was correlated to the cycle characteristics length (r = 0.941, P = 0.005), rate (r = −0.853, P = 0.031) and time...
Table 3 The activities of arm and leg muscles during the entire cycle and the poling and recovery phases of the first and second sessions of DIA and the DP skiing at 90% of VO2max/peak

|                                | First session of DIA | Second session of DIA | F-value | P-value | Power |
|--------------------------------|----------------------|-----------------------|---------|---------|--------|
| IEMG for the entire cycle arms (%MVCs) | 29.1 ± 9.2 | 25.7 ± 11.1 | 27.7 ± 8.0 | F(2,14) = 9.29 | 0.004 | 0.932 |
| IEMG for the entire cycle legs (%MVCs) | 16.1 ± 3.5 | 11.6 ± 3.8 | 16.0 ± 3.2 | F(2,14) = 15.64 | 0.007 | 0.906 |
| EMGbasal poling phase, arms (%MVC) | 72.9 ± 8.9 | 99.7 ± 12.9 | 66.6 ± 10.7 | F(2,14) = 6.66 | 0.042 | 0.580 |
| EMGbasal push-off phase legs (%MVC) | 44.6 ± 3.5 | 43.0 ± 3.6 | n.s. | F(2,14) = 1.13 | n.s. | n.s. |
| EMGbasal recovery phase, arms (%MVC) | 14.2 ± 2.4 | 14.5 ± 3.1 | 15.1 ± 2.2 | F(2,14) = 39.5 | 0.001 | 1.000 |
| EMGbasal recovery phase, legs (%MVC) | 31.4 ± 2.3 | 18.0 ± 2.8 | 30.5 ± 2.0 | F(2,14) = 51.1 | 0.001 | 1.000 |
| EMGbasal ratio, entire cycle, arms/whole body (%) | 25.1 ± 1.6 | 16.9 ± 2.4 | 24.2 ± 1.5 | F(2,14) = 13.0 | 0.001 | 0.984 |

The values presented are means ± SD. IEMG, integrated EMG; EMGbasal, EMG root mean squared; MVC, maximal voluntary contraction. A Two-Way repeated ANOVA (3 × 2) was used to compare the responses during the two sessions of DIA and DP. Since there was no push-off phase for the legs during DP, a 2 × 2 Two-Way repeated ANOVA was used to compare the EMGbasal for the poling and push-off phases. A One-Way repeated ANOVA was used in the case of the EMGbasal ratio and Bonferroni correction was used to compare different time-points, with paired Student’s t-test instead when only two time-points were compared.

*Significantly different from DIA,
#Significantly different from DIA,
†Significantly different from DP.
§Main effect: exercise intensity.
Main effect: extremity.
Interactive effect: exercise intensity x extremity.

(r = 0.865, P = 0.026), as well as absolute recovery time during the poling phase (r = 0.850, P = 0.032).

Overall extraction of O2
O2 extraction was higher in the legs than the arms at all workloads (F1,7 = 25.9, P = 0.002) and was lower in all limbs during DP than the two session of DIA (F2,14 = 10.3, P = 0.002 and F2, 14 = 10.4, P = 0.002, respectively), with no difference between the latter (leg P = 1.00 and arm P = 0.21). There was an interaction between skiing technique and sampling site (F2,14 = 3.89, P = 0.05), which might reflect the more pronounced reduction in O2 extraction in the arms during DP than both sessions of DIA (F2,14 = 13.31, P = 0.001) (Figure 3).

Blood levels of lactate and pH
The arterial-venous difference in blood level of lactate in the legs was lowest (actually negative) during DP and similar during both sessions of DIA (F2,14 = 5.92, P = 0.014). In contrast, in the case of the arms this difference remained constant (F2,14 = 2.17, P = 0.163) (Figure 4). The absolute blood level of lactate rose from the first session of DIA to DP and again to the second session of DIA, being significantly higher in the subclavian vein than in the femoral vein during all three sessions, with the lowest values for all sampling sites occurring during the second session of DIA (P < 0.01). The PCO2 remained constant throughout the test and was higher in both the femoral and subclavian vein than the femoral artery (P < 0.05) (Table 4).

The breathing pattern
During DP the cycle and breathing rates were tightly coupled (i.e. entrainment), with 52 breaths · min−1 (0.87 Hz) being similar to the cycle rate (a ratio of 1:1) (r = 0.89, P = 0.007). In the case of DIA, the rate of breathing was similar to the cycle rate during the first session (approximately 0.79 Hz), but greater than cycle rate during the second (0.88 Hz vs. 0.78 Hz, P = 0.022). Furthermore, there was no correlation between the breathing and cycle rates during either session of DIA (r = 0.23 and r = 0.18 both P > 0.05).

Discussion
The major findings of the study using repeated high-intensity DIA bouts interspersed with high-intensity DP were: 1) DP did not alter the redistribution in muscle activation between arms and legs and any further biomechanical variables between DIA1 and DIA2. 2) O2 extraction in both arms and legs was unaffected by DP as O2 extraction was unchanged between DIA1 and DIA2. However, arm O2 extraction decreased during DP compared to DIA despite higher muscle activation, a
three-fold increase in pole ground reaction force and an augmented blood lactate concentration in the arms. 3) Leg $O_2$ extraction was related to a greater unloading of the lower body by a more dynamic lower body work during DP and both DIA, while arm $O_2$ extraction was associated with cycle characteristics (e.g., cycle length, cycle rate, swing time) for DP only. Interestingly, a greater ratio of upper- to whole-body muscle activation at both DIA$_1$ and DIA$_2$ was associated with an attenuated arm $O_2$ extraction. 4) Pulmonary VO$_2$ did not increase over time as VO$_2$ for DIA$_1$ and DIA$_2$ was similar. However, there was an apparent acid base disturbance from DIA$_1$ to DIA$_2$ reflected by a decrease in pH, bicarbonate and an increase in lactate both systemically and for venous arm and leg blood.

**Effects of DP on upper to lower body muscle activation during DIA**

Despite increased muscle activation and peak pole forces during DP compared to DIA (~ +40%, +185%) no changes in regards of muscle activation distribution between upper- and lower-body and cycle characteristics for DIA$_2$ compared to DIA$_1$ were induced. Previous data from repeated sprint cross-country skiing on snow, using a higher exercise intensity than in the current study, demonstrated a decrease in upper body force and power output during DP (Zory et al. 2009). This decrease was accompanied by a decrease in performance. Our study was carried out on a treadmill using preset velocities where the skier was not able to adjust the velocity. However, this does not explain the absence in redistribution between upper and lower

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**Figure 2** The relationship between extraction of $O_2$ in the arms and the ratio of upper- (UB) and whole-body EMG$_{RMS}$ during the first (A) (DIA$_1$) and second sessions (B) (DIA$_2$) of diagonal stride skiing.
body as both arms and legs are used for propulsion during DIA. Also, it could be that the intensity was not strenuous enough for these well-trained skiers in accordance with a previous report that elite athletes withstand fatigue better to maintain neuromuscular control (Bonacci et al. 2011). Furthermore, the increased muscle activation during DP compared to DIA was specifically during the poling phase while for the entire movement cycle as well as the recovery phase no difference was observed. Therefore, even though the high demands on the upper body during high-intensity DP the upper-body contribution during DIA seems to be too small to necessitate a redistribution of upper to lower body work.

**O₂ extraction DP vs. DIA**

One of the novel findings was the decreased arm O₂ extraction during DP compared with DIA, although increased upper-body muscle activation (up to ~100% of MVC in DP vs. 70% of MVC in DIA). The result of a lower arm O₂ extraction during DP than DIA have previously been demonstrated by Calbet et al. (2005) using a lower exercise intensity (76 vs. 90% of VO₂max/peak).

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**Figure 3** O₂ extraction in the arms and legs during the first and second sessions of diagonal stride skiing and the intervening double poling at 90% VO₂max/peak. The values presented are as means ± SD. The P-values, effect size (η²), and observed power obtained with the two-way ANOVA (skiing technique × extremity) are presented. ***P < 0.001 in comparison to DP and †††P < 0.001 in comparison to the arms.

**Figure 4** The arterial-venous difference in blood levels of lactate in the legs and arms during the first and second sessions of diagonal stride skiing and the intervening double poling at 90% VO₂max/peak. The values presented are means ± SD. The P-values, effect size (η²), and observed power obtained with the two-way ANOVA (skiing technique × extremity) are presented. *P < 0.05 in comparison to DP and †††P < 0.001 in comparison to the legs.
Table 4 Lactate, pH and gases in the blood during roller-skiing with the diagonal stride (DIA) or double-poling (DP) technique at 90% VO₂max/peak

| Variable | Resting | First session of DIA | DP | Second session of DIA | F-values, P-values, observed power |
|----------|---------|----------------------|----|-----------------------|-----------------------------------|
| [Lactate], mmol · l⁻¹ |         |                      |    |                       |                                   |
| Femoral artery | 0.8 (±0.1) | 4.6 (±0.9) |
| Femoral vein | 0.7 (±0.2) | 4.7 (±0.8) |
| Subclavian vein | 0.8 (±0.3) | 6.3 (±1.4) |
| [Bicarbonate], mmol · l⁻¹ |         |                      |    |                       |                                   |
| Femoral artery | 23.6 (±1.9) | 19.2 (±1.0) |
| Femoral vein | 23.5 (±1.6) | 19.4 (±1.3) |
| Subclavian vein | 23.7 (±1.3) | 19.4 (±1.1) |
| pH |         |                      |    |                       |                                   |
| Femoral artery | 7.42 (±0.01) | 7.37 (±0.02) |
| Femoral vein | 7.38 (±0.02) | 7.27 (±0.02) |
| Subclavian vein | 7.37 (±0.03) | 7.24 (±0.03) |
| O₂ content, ml · l⁻¹ |         |                      |    |                       |                                   |
| Femoral artery | 190 (±15.2) | 193 (±15.3) |
| Femoral vein | 100 (±23.9) | 13.4 (±4.6) |
| Subclavian vein | 120 (±29.8) | 36.1 (±15.0) |
| SO₂ (%) |         |                      |    |                       |                                   |
| Femoral artery | 98.3 (±0.8) | 94.8 (±2.0) |
| Femoral vein | 51.1 (±11.1) | 6.5 (±24.2) |
| Subclavian vein | 57.0 (±17.9) | 16.9 (±7.5) |
| PO₂ (mm Hg) |         |                      |    |                       |                                   |
| Femoral artery | 111 (±15.2) | 77.3 (±10.8) |
| Femoral vein | 27.5 (±4.8) | 8.8 (±2.3) |
| Subclavian vein | 32.1 (±8.7) | 16.3 (±4.2) |
| PCO₂ (mm Hg) |         |                      |    |                       |                                   |
| Femoral artery | 34.9 (±4.0) | 30.5 (±2.6) |
| Femoral vein | 43.5 (±4.2) | 55.1 (±4.1) |
| Subclavian vein | 45.5 (±5.3) | 60.3 (±7.0) |

The values shown are means (±SD). PO₂, partial pressure of oxygen; PCO₂, partial pressure of carbon dioxide; SO₂, oxygen saturation.

*Main effect between intensities. †Significantly different to femoral artery. ‡Significantly different to DP90%.
*Main effect between sampling sites. *Significantly different to femoral vein. †Significantly different to DIA90%.

Furthermore, there was an interaction effect caused by a more pronounced decrease in O₂ extraction in arms than legs when switching from DIA₁ to DP and back to DIA₂. The reason for a lower arm O₂ extraction during DP has been shown, at least in part, to be due to a possible mechanical hindrance caused by high pole force generation and high arm muscle activity (~96% MVC) that hinders further elevation of O₂ extraction (Stöggł et al. 2013). The current study supports this finding, based on the reduction in arm O₂ extraction despite increased pole forces and upper body muscle activation when comparing DP with DIA.

Another explanation for the attenuated arm O₂ extraction during DP could be the decrease in total activated muscle mass, as reflected by the increased sum IEMG and AEMG values during DIA compared to DP. Mortensen et al. (2008) demonstrated that when activating a larger muscle mass (two-legged supra maximal cycling compared with one-legged exercise), locomotor skeletal muscle perfusion leveled off with a concomitant larger increase in O₂ extraction. Furthermore, comparisons between arm cycling vs. combined arm and leg cycling shows a decrease in arm blood flow when adding leg to arm exercise but at the same time increased O₂ extraction.
in the arms (Volianitis and Secher 2002). More specifically, in a study by Calbet et al. (2004) arm blood flow was substantially higher using DP than DIA although at a similar cardiac output. Therefore, in the current study high-intensity DIA likely induce additional central cardiovascular stress due to an increased activated total muscle mass than DP – as demonstrated by the augmented sum IEMG and AMEG values - and thus induces a higher \( O_2 \) extraction in both arms and legs to match the increased \( O_2 \) demand.

**Relationships between biomechanical variables and \( O_2 \) extraction**

Skiers who unloaded their legs to a greater extent (leg force minima) at the end of the gliding phase prior to leg push-off during DIA and prior to pole plant during DP extracted more \( O_2 \) in the legs. The last finding is in accordance with a previous study from our group where leg force minima was related to both \( O_2 \) extraction in the legs and arms at 90% and 70% of \( V\text{O}_{2\text{peak}} \) during DP (Stöggl et al. 2013). Furthermore, this result fits nicely with the previous demonstration that modern DP involves more dynamic use of the lower body: a higher body position prior to pole plant; greater extension of the knee, hip and ankle joints; and distinct knee and hip flexion during the poling phase (Holmberg et al. 2005). In addition Stöggl et al. (2010) demonstrated that faster skiers had greater center of mass oscillation in vertical direction during DP and DIA being coupled with a more active and dynamic skiing technique. The aspect about coupling between greater unloading of the legs prior to the push-off phase during DIA and leg \( O_2 \) extraction is novel. Therefore, more technically skilled skiers with more active and dynamic technique achieve a better \( O_2 \) extraction.

Arm \( O_2 \) extraction was negatively associated to cycle rate and positively related to cycle length and arm recovery time during DP, being in line with our previous findings during DP (Stöggl et al. 2013). This association between the decreased arm \( O_2 \) extraction and cycle rate during DP might be influenced by coupling to limb blood flow. Accordingly, an increased cycle rate might increase the centrifugal force that amplifies the arm blood flow as shown in another study using arm exercise at a similar cycle rate as in the current study (0.75 Hz) (Sheriff et al. 2009). There is further support that an increased contraction frequency (in our case cycle rate) induces a greater muscle blood flow (Ferguson et al. 2001; Sheriff 2003). Possibly the increased cycle rate could induce a higher arterial pressure that increase or maintains a high blood flow although usually such a high muscle activity shown in the current study restricts blood flow (70–100% of MVC). For the legs on the other hand no relationship was noticed between cycle rate and leg \( O_2 \) extraction which is in accordance with previous findings using isolated leg exercise (Ferguson et al. 2001).

**Excess \( \text{VO}_2 \), muscle activation and lactate**

It is suggested that it is not possible to perform a constant work rate at higher intensities that refers to a specific percent of \( \text{VO}_{2\text{max}} \) (Whipp 1994). One of the mechanisms proposed for this \( \text{VO}_2 \) slow component is the magnitude and the time course of the increase in lactate, i.e. above the lactate threshold (Burnley and Jones 2007). In contrast to that, in the current study no changes in \( \text{VO}_2 \) were found between DIA\(_1\) and DIA\(_2\) even though blood lactate steadily increased throughout the protocol (arterial: 4.6 to 7.9 mmol\( \cdot \)l\(^{-1}\)). Comparable results were found in the study of Björklund et al. (2011) also demonstrating no increase in \( \text{VO}_2 \) in world class cross-country skiers, when utilizing a variable intensity protocol containing 3 minutes exercise intensity of 90% of \( \text{VO}_{2\text{max}} \) interspersed with 6 minutes of 70% of \( \text{VO}_{2\text{max}} \) with a total duration of 24 min.

One reason for the absence of a raise in \( \text{VO}_2 \) from DIA\(_1\) to DIA\(_2\) in the current study might be due to the large amount of activated muscle mass and also already high \( O_2 \) extraction (~90%) with DIA and DP making the potential for a further increase in \( \text{VO}_2 \) diminutive.

**Respiration locomotion coordination**

While the exercise intensity was similar between the two DIA bouts there was a shift in breathing pattern. First, \( V_E \) increased for the second DIA due to an increase in \( B_f \) (47 vs. 53 breaths \( \cdot \)min\(^{-1}\)) while no change in tidal volume. This is in accordance with previously shown data using DIA although at a lower exercise intensity (~76% \( \text{VO}_{2\text{max}} \)) (Holmberg and Calbet 2007). Second, during the first DIA the \( B_f \) was similar as cycle rate (approximately 0.79 Hz), but at the second DIA workload there was a tachypneic shift, due to the elevated \( V_E \) caused by an increased \( B_f \) with a mean ratio of 1.13:1, (range 1:1 – 1.4:1) \( (B_f 0.88 \text{ Hz vs. cycle rate 0.78 Hz}) \). The cause for this asynchronic \( B_f \) to cycle rate ratio during DIA\(_2\) could be explained by the increased metabolic acidosis as the arterial blood lactate concentration went from 4.6 to 7.9 mmol\( \cdot \)l\(^{-1}\) and the pH dropped from 7.37 to 7.31 between DIA\(_1\) to DIA\(_2\). However the skiers \( P_a\text{CO}_2 \) remained fairly stable and did not show signs of hypercapnia, nor was there a relation between the magnitude of asynchronous breathing and \( P_a\text{CO}_2 \).

Further, even though \( B_f \) increased between DIA\(_1\) and DIA\(_2\) the \( B_f \) remained unchanged between DP and DIA\(_2\), although the latter of the two was performed with a lower cycle rate. The coordination between respiration – locomotion was therefore not fixed for DIA. However the breathing pattern in the current study confirms that during the single bout of DP there was a tight coupling between cycle rate and \( B_f \) i.e. entrainment, with a \( B_f \) of 52 breaths \( \cdot \)min\(^{-1}\) equaling 0.87 Hz being similar to the cycle
and cycle rate was 2max/peak 18 km · h−1. This 1:1 coupling could be exercise intensity dependent as shown previously during DP using a fixed cycle rate of 60 Hz were Bf and cycle rate was uncoordinated for lower speeds (12–18 km · h−1) while attaining a 1:1 ratio during 24 km · h−1 (Lindinger and Holmberg 2011).

**Limitations**

Due to the lack of blood flow measurements it cannot be definitively concluded whether the differences in O2 extraction between the arms and legs and between DP and DIA are due to differences in blood flow and/or metabolic demands. Further arterial blood pressure measurements could add information regarding the effect of arm swing and cycle rate influence of both O2 extraction and blood flow. This link was especially pronounced during mainly upper-body work, i.e. DP in the current study.

**Conclusions**

In well trained skiers, DP does not influence DIA VO2, at a simulated race intensity of ~90% of VO2max/peak. Furthermore, although high-intensity DP induce substantially higher arm muscle activation concurrent with a three-fold increase in pole force compared to DIA, it does not affect the redistribution of pole and foot forces, cycle characteristics and cardiorespiratory characteristics during the following DIA bout. This suggests that well trained skiers withstand the upper-body strain that high-intensity DP implies. The absence of an increase in VO2 from DIA1 to DIA2 despite a distinct increase of blood lactate questions the relation between blood lactate and O2 extraction in DIA, while DP: Double poling; DP: Maximal oxygen uptake; VO2peak: Peak oxygen uptake.

**Competing interests**

The authors declare that they have no competing interests.

**Authors’ contributions**

GB and HH participated in the critical conception and design of the work; GB and TS performed the acquisition of data and analysis (physiological and biomechanical data respectively); GB, HH and TS performed the interpretation of data, drafting the work and revising it critically for important intellectual content and final approval of the version to be published and agreement to be accountable for all aspects of the work.

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