

## How do elite cross-country skiers adapt to different double poling frequencies at low to high speeds?

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**Abstract** The purpose of the study was to examine the biomechanical-physiological effects of different frequencies using the double poling technique in cross-country skiing. Nine elite skiers roller-skied using poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> (Pf<sub>40</sub>, Pf<sub>60</sub>, Pf<sub>80</sub>) at submaximal treadmill speeds (12, 18, 24 km·h<sup>-1</sup>). Cycle characteristics, pole forces, joint angles and physiological responses were measured. Comparing Pf<sub>40</sub> versus Pf<sub>60</sub> versus Pf<sub>80</sub> (all variables different at  $P < 0.05$ ), absolute poling time decreased by up to 46%, as did absolute and relative (% cycle time) recovery times, at almost all speeds. Peak force, impulse of force and time to peak force decreased, whereas impact force increased with frequency at almost all speeds. Elbow ranges of motion and angular velocities, hip and knee angle maxima and flexion/extension ranges of motion per cycle decreased, whereas hip and knee angle minima, ranges of motion per minute and angular extension velocities during recovery phase all increased with frequency at nearly all speeds. Oxygen uptake and heart rate increased up to 13% (Pf<sub>40-60</sub> versus Pf<sub>80</sub>) at all speeds. Pulmonary ventilation increased most

distinctly at the highest speed. Blood lactate was lowest at Pf<sub>60</sub> and highest at Pf<sub>80</sub> (J-shape curve) at 24 km·h<sup>-1</sup>. Gross efficiency decreased with higher frequency at all speeds. These results demonstrate different biomechanical and physiological demands at different frequencies with the beneficial effects of lower poling frequencies at submaximal speeds. For training purposes, we suggest that cross-country skiers would benefit by training with different poling frequencies to vary their training load.

**Keywords** Biomechanics · Cadence · Kinematics · Kinetics · Lactate · Oxygen cost

### Introduction

Early studies on speed control and cycle characteristics in double poling and other cross-country skiing techniques (Hoffman et al. 1995; Millet et al. 1998b; Nilsson et al. 2004; Smith 2002) emphasized that speed, the product of cycle length and frequency, was mainly increased by a rise in poling frequency, whereas cycle length increases were performed to a smaller extent and only up to medium speeds of ~15–18 km·h<sup>-1</sup>. In contrast, Lindinger et al. (2009c) showed that modern elite skiers control speed by both increases in poling frequency and cycle length up to considerably higher speeds (~27 km·h<sup>-1</sup>), a strategy related to modern, more dynamic double poling with generation of higher forces during more dynamic flexion/extension patterns in upper body and leg joints (Holmberg et al. 2005; Lindinger et al. 2009b). The role of frequency in speed control leads to the important question of how elite cross-country skiers adapt to different double poling frequencies at different constant speeds, a topic that has been rarely analysed in cross-country skiing (Millet et al.

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1998a) but was extensively explored in other endurance sports with frequency found to be a crucial factor for performance (for refs see Marais and Pelayo 2003; Ver-cruyssen and Brisswaller 2010). This lack of studies examining frequency is somewhat surprising because frequency choice may affect performance and efficiency and is extra challenged in cross-country skiing due to the constant variation in terrain and velocity as well as different external conditions.

Double poling requires that skiers repetitively flex their upper body, e.g.  $\sim 70\%$  of body mass (Winter 1990), over a hip flexion/extension range of motion of  $\sim 70^\circ$  (Holmberg et al. 2005) which may indicate a significant internal work at high poling frequencies. Classical studies of other locomotion's demonstrate that the movement of the extremities per se constitute a significant part of the metabolic cost during e.g. running (Cavagna et al. 1964) and experiments in running and walking, where an extra weight has been added distally on the foot or ankle, have shown increased energy consumption (Griffin et al. 2003; Myers and Steudel 1985). Hence, it is not only the application of force through the poles against the ground, but also different degrees of range of motion in order to position and re-position the upper body that may influence the total oxygen consumption in double poling. The amount of energy needed for this inner work may increase with poling frequency.

The aims of the present study were to examine elite cross-country skiers' (1) biomechanical adaptations and (2) physiological responses, to different poling frequencies at low, medium and high speeds. The hypothesis to be tested was that cross-country skiers generate higher forces using greater ranges of joint motion at lower, compared to higher, poling frequencies, also leading to a lower aerobic demand.

## Methods

### Subjects

Nine Swedish top-elite cross-country skiers (mean  $\pm$  SD: age  $22 \pm 2$  year, height  $182 \pm 8$  cm, and body weight  $79 \pm 7$  kg) volunteered to participate in the study. The subjects had a maximal oxygen uptake ( $VO_{2max}$ ) of  $5.5 \pm 0.5$  L $\cdot$ min $^{-1}$  (range 4.8–6.5 L $\cdot$ min $^{-1}$ ) corresponding to  $70.2 \pm 3.4$  mL $\cdot$ kg $^{-1}\cdot$ min $^{-1}$  (range 66.0–76.4 mL $\cdot$ kg $^{-1}\cdot$ min $^{-1}$ ).  $VO_{2max}$  was measured during an incremental test to exhaustion according to the standard protocol of the Swedish National Team and using the diagonal stride technique while skiing uphill with roller skis (PRO-SKI C2, Nyhammar, Sweden) on a treadmill (Rodby, Vänge, Sweden), as previously described (Lindinger et al. 2009a, b). All subjects were informed about the possible risks and discomfort involved before giving their written consent to participate.

This study was carried out according to the Declaration of Helsinki, and pre-approved by the Ethics Committee of Umeå University, Umeå, Sweden (#06–160 M).

### Overall design of the study

The study was composed of three separate series of tests including: (1) a diagonal skiing  $VO_{2max}$  test as described above (one test day); (2) physiological tests to analyse frequency responses at different speeds (three test days) and (3) biomechanical tests (one test day) to investigate frequency effects on the biomechanical characteristics of double poling. All test series were performed on five separate days in a randomized order over a 21-day period. The diagonal skiing  $VO_{2max}$  test was performed on a separate day in order to characterize the participating subjects. In another test series, the physiological frequency response was analysed at three double poling frequencies of 40, 60 and 80 (Pf<sub>40</sub>, Pf<sub>60</sub>, Pf<sub>80</sub>) cycles $\cdot$ min $^{-1}$  (0.67, 1.00 and 1.33 Hz), when roller skiing on a treadmill at a common inclination of  $1^\circ$  (Holmberg et al. 2005; Lindinger et al. 2009c; Mittelstadt et al. 1995). For each of the three frequencies, separate incremental tests, including three 4-min double poling increments at the speeds of 12, 18 and 24 km $\cdot$ h $^{-1}$ , were performed. These three physiological frequency tests were carried out on three different days in a randomized order with 48-h intervals in between, but at the same time of day. The frequencies during the physiological tests were governed by a digital metronome (Korg kdm-2, Korg Corp., Tokyo, Japan). In a third and separate test series (one test day), the effects of Pf<sub>40</sub>, Pf<sub>60</sub> and Pf<sub>80</sub> on biomechanical double poling characteristics were analysed at the same three speeds (12, 18 and 24 km $\cdot$ h $^{-1}$ ) and under the same laboratory conditions (treadmill; inclination; roller skis; metronome control, etc.). In all biomechanical trials, 30 valid double poling cycles at the corresponding frequency and speed were measured (randomized trial order on 1 day). A break of 4 min between each trial was taken for fatigue prevention purposes. Prior to physiological as well as biomechanical measurements, a standardized warm up of 20 min was performed with double poling at 60–75% of each skier's maximum speed using the analysed poling frequencies of Pf<sub>40</sub>, Pf<sub>60</sub> and Pf<sub>80</sub>. Of note is that due to the preset increasing frequencies (Pf<sub>40</sub>–Pf<sub>80</sub>) during all tests, skiers were forced to create the following decreasing cycle lengths of 5.00, 3.33 or 2.50 m at 12 km $\cdot$ h $^{-1}$ , 7.50, 5.00 or 3.75 m at 18 km $\cdot$ h $^{-1}$ , and finally 10.00, 6.67 or 5.00 m at 24 km $\cdot$ h $^{-1}$  to manage the given treadmill speeds.

### Roller skis and treadmill

All subjects used the same pair of classical roller skis (Pro-Ski C2, Sterners, Nyhammar, Sweden), in order to exclude

variations in rolling resistance. A standardized method of friction measurements used in our laboratory has previously been described in detail by Ainegren and Carlsson (2008), showing no differences between treadmill speeds (8–28 km·h<sup>-1</sup>). The rolling resistance friction coefficient ( $\mu_R$ ) was measured on the treadmill surface and 0.024 was determined as an appropriate value for further calculations. All the roller ski tests were performed on a large ski treadmill (Rodby, Sodertalje, Sweden) with belt dimensions of 3.3 × 2.5 m. All subjects were familiar with roller skis as tools for their normal training and testing and were used to training at the poling frequencies used in the study. During all the tests, the subjects were secured with a safety harness suspended from the ceiling.

### Physiological measurements

Pulmonary VO<sub>2</sub>, CO<sub>2</sub> production (VCO<sub>2</sub>) and expired minute ventilation (V<sub>E</sub>) were measured continuously during all tests using an ergo-spirometry system (AMIS 2001 Innovision A/S, Odense, Denmark). The gas analysers and the flowmeter were calibrated before each test. The gas analyser was calibrated using high-precision gases of known concentrations (16.00 ± 0.04% O<sub>2</sub> and 4.00 ± 0.1% CO<sub>2</sub>, Air Liquide, Kungsängen, Sweden). The calibration of the pneumotach was performed with a precision 3 L calibration syringe for low-, medium- and high-flow volumes (Hans Rudolph, Kansas City, MO, USA). VO<sub>2</sub> values were calculated and averaged during the final minute of each 4 min submaximal work bout. VO<sub>2max</sub> in the diagonal skiing test was calculated as the average of the three consecutive, highest 10-s measurements of O<sub>2</sub> uptake during the last min of exercise to exhaustion. Heart rate was measured using a heart rate monitor (model Polar S610, Polar Electro OY, Kempele, Finland) with the metabolic cart heart rate receiver. Capillary blood samples (20 µL) were taken from the fingertip and used for determination of blood lactate concentration [BLa] by Biosen 5140 (EKF-diagnostic GmbH, Magdeburg, Germany).

### Biomechanical measurements

#### *Pole forces*

All skiers used telescopically adjustable carbon racing poles, specifically constructed for axial force measurements. Axial ground reaction forces at the right pole were recorded (3,000 Hz) by a uniaxial strain gauge load cell (Biovision, Werheim, Germany; range 0.5–10 kN, weight 15 g) embedded in a lightweight (56 g) aluminium body mounted in the carbon tube directly below the grip. The load cell was calibrated by using standard weights (5–50 kg) placed on an iron platform, mounted above the

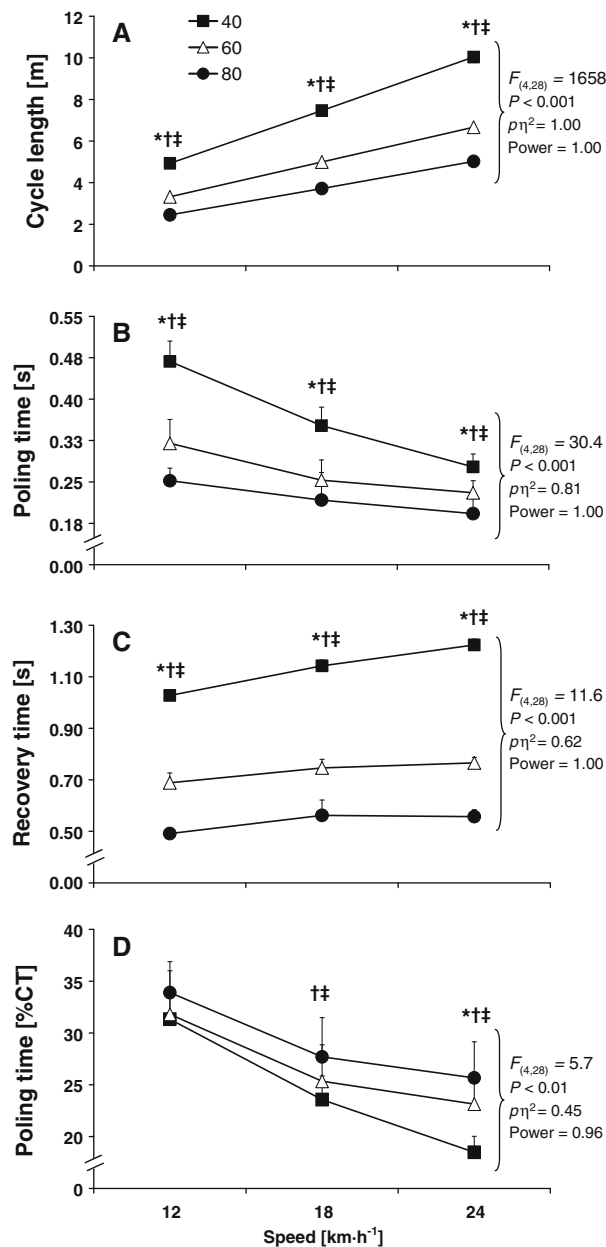
measuring unit and perpendicular to the pole's tube during calibration. The validation of the system was performed by a comparison with AMTI force plate data (AMTI, Watertown, MA, USA) during 30 double poling thrusts (Holmberg et al. 2005; Lindinger et al. 2009c) with a mean absolute error of 2.9%. Cycle characteristics (Fig. 1a–d) and pole force data like impact force at pole plant, peak pole force, time to peak pole force, mean rate of force development (from local force minimum after impact up to peak pole force) and the impulse of pole force (Fig. 2a–f) were determined and calculated from force curves (Fig. 3). All force variables were calculated in absolute (N) and relative (% body weight [BW]) values.

#### *Joint angles*

Elbow, hip and knee joint flexion and extension angles were measured (3,000 Hz) by flexible electrogoniometers with an indicated accuracy of ±2° measured over a range of ±90° and a repeatability of 1° measured over a range of 90° (Biometrics LTD UK, Cmwfelinbach, Gwent, UK). Calibration measurements were performed five times at 90°, as well as at 180°, for all joints, and angle values were calculated from the corresponding mean voltage data that showed linear relationships. A 90° angle corresponded to the forearm perpendicular to the upper arm, the thigh perpendicular to the trunk and the lower leg perpendicular to the thigh. A 180° angle corresponded to fully extended elbow and knee joints and the thigh aligned with the trunk. All joint angle variables were collected and calculated from joint angle curves for each cycle. The joint angles were measured at specific movement events like pole plant, end of pole ground contact, minimum and maximum angle during poling and recovery phase. Elbow flexion was defined as the phase from pole plant to the elbow angle minimum during poling phase and elbow extension from minimum to the end of pole ground contact. Hip and knee flexion and extension were defined as the phase from (1) the respective angle maximum during the recovery phase, shortly before pole plant down to the angle minimum during the poling phase (pole ground contact) and (2) from this minimum back up to the angle maximum during the recovery phase. Mean angular velocities for all joints were calculated as the flexion/extension ranges of motion divided by the flexion/extension times.

#### *Cycle characteristics and phase definitions*

One double poling cycle was defined as the phase from pole plant to the subsequent pole plant and was further divided into the poling (ground contact) and recovery phase (poles off the ground). Demonstrated cycle characteristics at each predetermined speed and frequency were



**Fig. 1** Cycle length (a), absolute poling time (b), recovery time (c) and relative poling time (d) at poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> at submaximal treadmill speeds of 12, 18 and 24 km·h<sup>-1</sup>. The data are mean + SD ( $n = 9$ ).  $F$  values,  $P$  values, partial eta square effect size ( $\eta^2$ ) and power are presented for two-way ANOVA (frequency \* speed). \*Difference 40–60 cycles·min<sup>-1</sup>; † Difference 40–80 cycles·min<sup>-1</sup>; ‡ Difference 60–80 cycles·min<sup>-1</sup>.  $P < 0.05$

calculated from pole force data and specified as cycle time (CT), absolute (s) and relative (%CT) poling and recovery time (PT; RT), poling frequency ( $Pf = 1 \cdot CT^{-1}$ ) and cycle length ( $CL = CT \cdot \text{velocity}$ ). All biomechanical data in the study were averaged over fifteen cycles for each subject and situation.

#### Gross efficiency, work rate and metabolic rate calculations

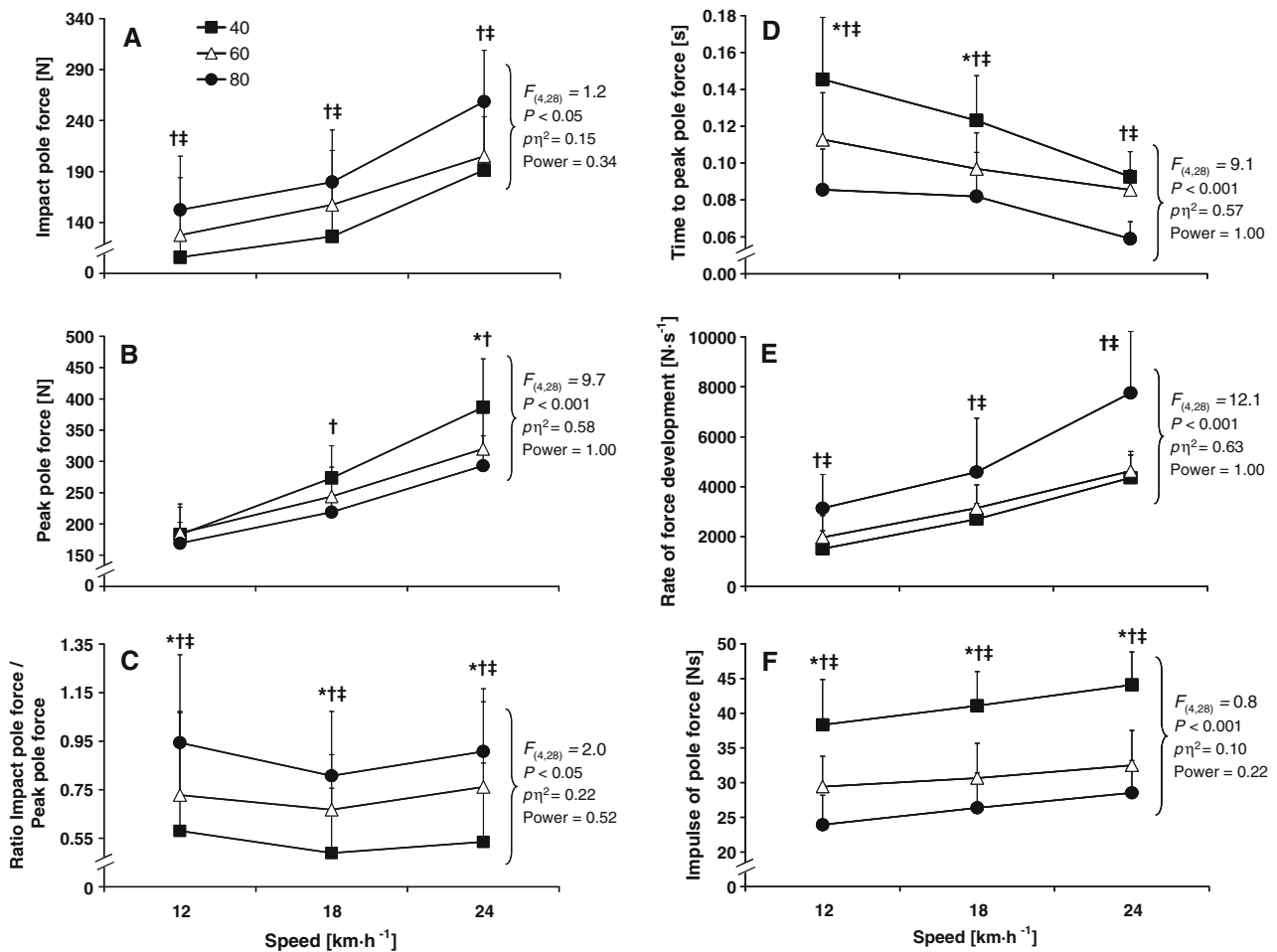
Gross efficiency was calculated as work rate divided by metabolic rate, according to Sandbakk et al. (2010). Work rate was calculated as the sum of the power against rolling friction ( $P_f$ ) and the power against gravity ( $P_g$ ). The power against friction was calculated as the work against friction at a given speed ( $P_f = \mu \cdot m \cdot g \cdot \cos(\alpha) \cdot v$ ), with  $v$  being belt speed and  $\alpha$  the angle of incline. Power against gravity was calculated as the increase in potential energy per time ( $P_g = m \cdot g \cdot \sin(\alpha) \cdot v$ ). The metabolic rate (MR) was calculated as the sum of aerobic and anaerobic MR. The aerobic MR was determined from  $VO_2$  and  $VCO_2$ , by calculating the product of  $VO_2$  and the oxygen energetic equivalent, using the associated measurements of respiratory exchange ratio (RER) and standard conversion tables (Peronnet and Massicotte 1991). The anaerobic MR was calculated from the obtained BLA values measured directly after each condition (speed and frequency). A 1 mmol·L<sup>-1</sup> of BLA was regarded as equivalent to 3 mL·kg<sup>-1</sup> of oxygen consumed at an RER = 1.0 (di Prampero and Ferretti 1999).

#### Data collection and data analysis

Pole force and joint angle data were amplified by using a telemetric recording system (TeleMyo 2400T G2, Noraxon, Scottsdale, AZ, USA) and simultaneously recorded with a sampling rate of 3,000 Hz on a personal computer via an A/D converter card. The system consisted of a 16-channel transmitter unit, a USB-based PC-interface receiver box, battery charger and a belt clip combined with a pouch for fixation of the transmitter unit around the hips. For basic data analyses, Myoresearch software version 1.06.50 (Noraxon, Scottsdale, AZ, USA) was used. All physiological and biomechanical data were further analysed by Office Excel 2007 (Microsoft Corporation, Redmond, Washington, USA).

#### Statistical analysis

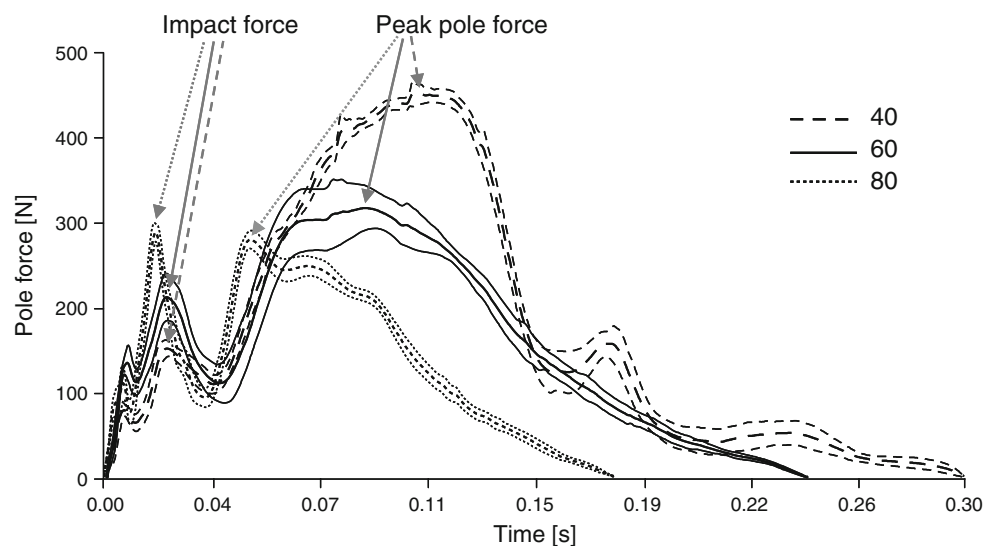
All data were checked for normality, calculated with conventional procedures and presented as means and standard deviations ( $\pm$ SD). A two-way repeated-measures ANOVA (poling frequency  $\times$  speed) was calculated to test global biomechanical and physiological differences between the three frequencies and the three speeds and to analyse interaction effects (frequency  $\times$  speed). In case of significant global differences between poling frequencies, a one-way repeated-measures ANOVA was conducted using a Bonferroni alpha correction. Variables were further evaluated by the calculation of the effect size using partial eta square ( $\eta^2$ ) and the statistical power. Statistical



**Fig. 2** Impact pole force (a), peak pole force (b), ratio impact to peak pole force (c), time to peak pole force (d), rate of force development (e) and impulse of pole force (f) at poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> at submaximal treadmill speeds of 12, 18 and 24 km·h<sup>-1</sup>. The data are mean + SD ( $n = 9$ ).  $F$  values,  $P$  values,

partial eta square effect size ( $\rho\eta^2$ ) and power are presented for two-way ANOVA (frequency \* speed). \*Difference 40–60 cycles·min<sup>-1</sup>; † Difference 40–80 cycles·min<sup>-1</sup>; ‡ Difference 60–80 cycles·min<sup>-1</sup>.  $P < 0.05$

**Fig. 3** Representative pole force curves at poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> at a treadmill speed of 24 km·h<sup>-1</sup>. Time courses are mean ± SD



significance was set at  $P < 0.05$  for all analyses. All statistical tests were processed using the SPSS 17.0 Software (SPSS Inc, Chicago, IL) and Office Excel 2007 (Microsoft Corporation, Redmond, WA).

## Results

### Biomechanical comparison at different poling frequencies

#### Cycle characteristics

Deviations between the preset and the actually performed, metronome-controlled double poling frequencies at all speeds were in the range of  $-0.4$  to  $0.8$  cycles·min<sup>-1</sup> ( $-0.6$  to  $0.9\%$ ). The skiers generated longer cycle lengths at Pf<sub>40</sub> versus Pf<sub>60</sub> as well as Pf<sub>60</sub> versus Pf<sub>80</sub> (all  $P < 0.001$ ) at all speeds, reaching a maximum of  $10.04 \pm 0.06$  m at Pf<sub>40</sub> and  $24$  km·h<sup>-1</sup> and a minimum of  $2.48 \pm 0.03$  m at Pf<sub>80</sub> and  $12$  km·h<sup>-1</sup> (Fig. 1a). Absolute poling and recovery time gradually decreased up to 46 and 54%, respectively, from low to high frequencies at all speeds (all  $P < 0.05$ ), indicating frequency-speed interactions ( $F_{(4,28)} = 30.4$ ;  $F_{(4,28)} = 11.6$ ; both  $P < 0.001$ ) and reaching a minimum poling time of  $0.19 \pm 0.03$  s at Pf<sub>80</sub> and  $24$  km·h<sup>-1</sup> (Fig. 1b, c). Relative poling and recovery time were shorter and longer, respectively at Pf<sub>40</sub> & <sub>60</sub> versus Pf<sub>80</sub> at  $18$  km·h<sup>-1</sup> and at Pf<sub>40</sub> versus Pf<sub>60</sub> versus Pf<sub>80</sub> at  $24$  km·h<sup>-1</sup> (all  $P < 0.05$ ), showing no differences at the lowest speed and demonstrating frequency-speed interactions ( $F_{(4,28)} = 5.7$ ,  $P < 0.01$ ). The minimum relative poling time was  $19 \pm 2\%$ CT and the maximum recovery time  $81 \pm 2\%$ CT, respectively, occurring at Pf<sub>40</sub> and  $24$  km·h<sup>-1</sup> (Fig. 1d).

#### Pole force

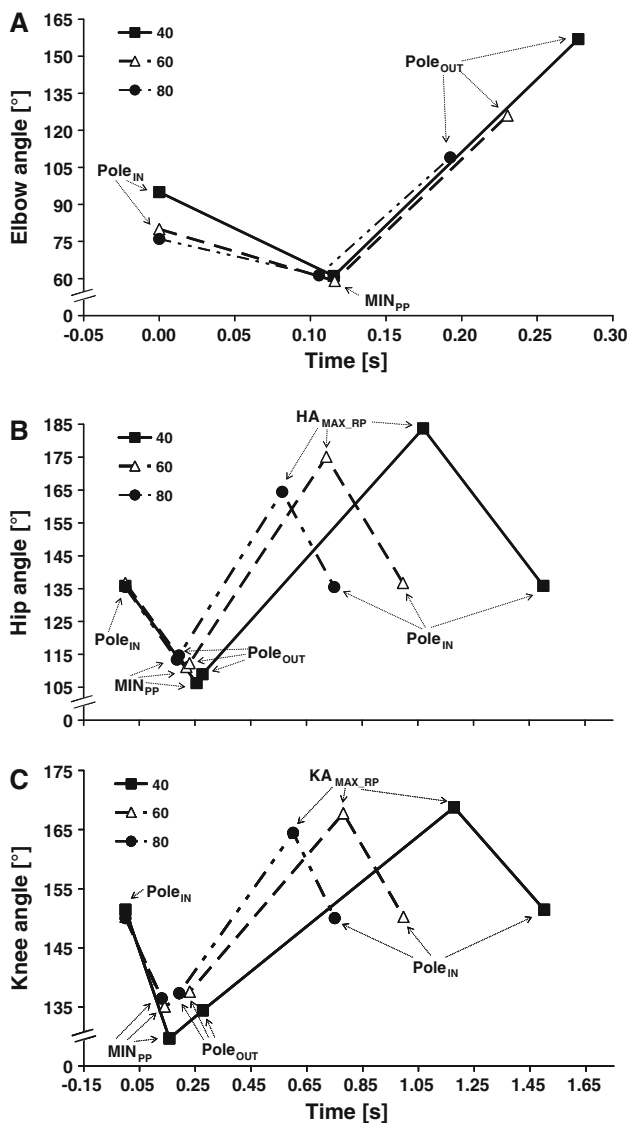
Changes in pole force variables are presented in Fig. 2a–f and Fig. 3. Impact force at pole plant was 15–44% lower for Pf<sub>40</sub> & <sub>60</sub> versus Pf<sub>80</sub> at all speeds (all  $P < 0.05$ ), indicating no frequency-speed interaction ( $F_{(4,28)} = 1.2$ ,  $P > 0.05$ ). Peak pole force did not show differences at the lowest speed, but skiers generated 20% higher pole force at Pf<sub>40</sub> versus Pf<sub>80</sub> at  $18$  km·h<sup>-1</sup> ( $P < 0.05$ ) and 17–24% higher forces at Pf<sub>40</sub> versus Pf<sub>60</sub> & <sub>80</sub> at  $24$  km·h<sup>-1</sup> (all  $P < 0.05$ ), showing a frequency-speed interaction ( $F_{(4,28)} = 9.7$ ,  $P < 0.001$ ). The ratio between impact and peak pole force gradually increased up to 70% from low to high poling frequencies at all speeds (all  $P < 0.05$ ), reaching the lowest ratios at Pf<sub>40</sub> (0.49–0.66) and the highest ones at Pf<sub>80</sub> (0.81–0.94) across all speeds and indicating no frequency-speed interaction ( $F_{(4,28)} = 2.0$ ,  $P > 0.05$ ). Time to peak pole force gradually decreased

16–41% from low to high poling frequencies at all speeds (all  $P < 0.05$ ) except from Pf<sub>40</sub> to Pf<sub>60</sub> at  $24$  km·h<sup>-1</sup>, reaching a minimum value of  $0.06 \pm 0.01$  s at Pf<sub>80</sub> and  $24$  km·h<sup>-1</sup> and indicating a frequency-speed interaction ( $F_{(4,28)} = 9.1$ ,  $P < 0.001$ ). The rate of force development was 46–107% greater at Pf<sub>40</sub> & <sub>60</sub> versus Pf<sub>80</sub> at all speeds (all  $P < 0.05$ ), demonstrating a frequency-speed interaction ( $F_{(4,28)} = 12.1$ ,  $P < 0.001$ ). Impulse of pole force gradually decreased up to 38% with increasing frequency (all  $P < 0.05$ ) at all speeds, with maximum values of  $44 \pm 5$  Ns at Pf<sub>40</sub> and  $24$  km·h<sup>-1</sup> and showing no frequency-speed interaction ( $F_{(4,28)} = 0.8$ ,  $P > 0.05$ ).

#### Joint angles

Changes in joint angle variables are reported in Fig. 4a–c and in Tables 1, 2, 3 including detailed statistics. Elbow angle at pole plant and the end of the poling phase was 11–39% greater at Pf<sub>40</sub> versus Pf<sub>60</sub> & <sub>80</sub> and Pf<sub>40</sub> versus Pf<sub>60</sub> versus Pf<sub>80</sub>, respectively, at all speeds (all  $P < 0.05$ ), with no changes in elbow angle minimum and without frequency-speed interactions for these variables ( $F_{(4,28)} = 0.6$ ;  $1.6$ ;  $0.6$ ; all  $P > 0.05$ ). Elbow flexion and extension ranges of motion gradually decreased 28–72% from one to the next higher frequency at almost all speeds (all  $P < 0.05$ ). These frequency differences in flexion range of motion increased from 12 to 18 and  $24$  km·h<sup>-1</sup>, but decreased from 18 to  $24$  km·h<sup>-1</sup>, indicating a frequency-speed interaction ( $F_{(4,28)} = 5.3$ ,  $P < 0.01$ ). Elbow flexion angular velocity was 30–67% greater at Pf<sub>40</sub> versus Pf<sub>60</sub> & <sub>80</sub> and elbow extension angular velocity 12–20% greater at Pf<sub>40</sub> & <sub>60</sub> versus Pf<sub>80</sub> at all speeds (all  $P < 0.05$ ). These frequency differences in flexion angular velocity increased with increasing speed (frequency-speed interaction:  $F_{(4,28)} = 14.3$ ,  $P < 0.001$ ).

As key hip and knee positions during a double poling cycle, the joint angle minima and maxima were up to 7% lower and up to 11% higher, respectively, at Pf<sub>40</sub> versus Pf<sub>80</sub> at almost all speeds (all  $P < 0.05$ ), whereby the hip angle maximum was also higher at Pf<sub>60</sub> versus Pf<sub>80</sub>. The frequency differences for hip angle at pole plant as well as knee angle minimum decreased and increased, respectively, with increasing speed (frequency-speed interactions:  $F_{(4,28)} = 8.8$ ,  $P < 0.01$ ;  $F_{(4,28)} = 5.3$ ,  $P < 0.05$ ). Hip and knee flexion/extension ranges of motion during one double poling cycle gradually decreased 14–45% from one to the next higher frequency at nearly all speeds (all  $P < 0.05$ ). These frequency differences in knee range of motion increased with increasing speed (frequency-speed interaction:  $F_{(4,28)} = 4.4$ ,  $P < 0.01$ ). Hip and knee flexion/extension ranges of motion calculated over 1 min were 10–33% smaller at Pf<sub>40</sub> versus Pf<sub>60</sub> & <sub>80</sub> at all speeds, with further increases from Pf<sub>60</sub> to Pf<sub>80</sub> only for the knee joint



**Fig. 4** Elbow (a), hip (b) and knee (c) angle at pole plant ( $Pole_{IN}$ ), angle minima during poling phase ( $MIN_{PP}$ ), angles at the end of poling phase ( $Pole_{OUT}$ ) and hip ( $HA_{MAX\_RP}$ ) and knee ( $KA_{MAX\_RP}$ ) angle maxima during recovery phase at poling frequencies of 40, 60 and 80 cycles $\cdot$ min $^{-1}$  presented for 24 km $\cdot$ h $^{-1}$ . The data are mean. All elbow, hip and knee joint variables as mean  $\pm$  SD are presented in Tables 1, 2, 3

(all  $P < 0.05$ ). These frequency differences in the hip joint increased with increasing speeds, showing a frequency-speed interaction ( $F_{(4,28)} = 6.3$ ,  $P < 0.01$ ) and reaching peak flexion/extension ranges of motion of  $8160 \pm 2228^{\circ}\cdot$ min $^{-1}$  when using  $Pf_{80}$  at 24 km $\cdot$ h $^{-1}$ . Angular flexion velocity in the hip and knee joints showed only minor changes between frequencies. In contrast, hip extension angular velocity was 23–51% smaller at  $Pf_{40}$  versus  $Pf_{60}$  & 80 and knee extension angular velocity 22–91% smaller at  $Pf_{40}$  versus  $Pf_{60}$  versus  $Pf_{80}$  at nearly all speeds (all  $P < 0.05$ ). The latter frequency differences for hip and knee increased from speed to speed, indicating

frequency-speed interactions ( $F_{(4,28)} = 12.4$ ,  $P < 0.001$ ;  $F_{(4,28)} = 3.4$ ,  $P < 0.05$ ).

#### Physiological comparison at different poling frequencies

The changes in physiological variables at different poling frequencies are presented in Fig. 5a–f. Oxygen uptake and heart rate were lower at  $Pf_{40}$  & 60 versus  $Pf_{80}$  at all speeds (all  $P < 0.05$ ), indicating no frequency-speed interactions ( $F_{(4,28)} = 3.0$ ;  $F_{(4,28)} = 1.8$ ; both  $P > 0.05$ ) with similar frequency differences at all speeds. Blood lactate concentration did not show any differences between frequencies at the two lower submaximal speeds. At 24 km $\cdot$ h $^{-1}$  blood lactate was lower at  $Pf_{60}$  versus  $Pf_{40}$  & 80 and lower at  $Pf_{40}$  versus  $Pf_{80}$  (all  $P < 0.05$ ), overall showing a frequency-speed interaction ( $F_{(4,28)} = 4.4$ ,  $P < 0.05$ ), with maximum values of  $5.61 \pm 0.85$  mmol $\cdot$ L $^{-1}$  at  $Pf_{80}$  and 24 km $\cdot$ h $^{-1}$ . The respiratory exchange ratio was lower at  $Pf_{40}$  & 60 versus  $Pf_{80}$  (all  $P < 0.05$ ) at 18 km $\cdot$ h $^{-1}$  ( $0.90 \pm 0.06$ ;  $0.91 \pm 0.05$ ;  $0.95 \pm 0.04$ ) and 24 km $\cdot$ h $^{-1}$  ( $0.96 \pm 0.05$ ;  $0.97 \pm 0.04$ ;  $1.03 \pm 0.05$ ) with no differences at 12 km $\cdot$ h $^{-1}$  ( $0.86 \pm 0.06$ ;  $0.86 \pm 0.06$ ;  $0.87 \pm 0.04$ ), showing no frequency-speed interaction ( $F_{(4,28)} = 1.8$ ,  $P > 0.05$ ;  $\eta^2 = 0.20$ ; Power = 0.47). Pulmonary ventilation was lower at  $Pf_{40}$  versus  $Pf_{80}$  at all speeds (all  $P < 0.05$ ), whereas a gradual increase from one to the next higher frequency was observed only at 24 km $\cdot$ h $^{-1}$  (all  $P < 0.05$ ), indicating a frequency-speed interaction ( $F_{(4,28)} = 15.0$ ,  $P < 0.001$ ). The ventilatory equivalents for oxygen ( $V_E/V_{O_2}$ ) and carbon dioxide ( $V_E/V_{CO_2}$ ) were lower at  $Pf_{40}$  versus  $Pf_{60}$  & 80 only at the highest speed (all  $P < 0.05$ ), demonstrating frequency-speed interactions ( $F_{(4,28)} = 5.6$ ,  $P < 0.01$ ;  $F_{(4,28)} = 5.0$ ,  $P < 0.01$ ). There were no mean differences in breathing frequency at the two lower submaximal speeds, but at 24 km $\cdot$ h $^{-1}$  skiers showed a lower breathing frequency at  $Pf_{40}$  versus  $Pf_{60}$  & 80 (all  $P < 0.05$ ), indicating a frequency-speed interaction ( $F_{(4,28)} = 5.8$ ,  $P < 0.05$ ). At  $Pf_{40}$ , all skiers showed a 1:1 locomotor-respiratory coupling pattern with breathing at  $40 \pm 4$  breaths $\cdot$ min $^{-1}$  across all speeds. At  $Pf_{60}$ , all skiers changed to a  $\sim$ 1:1 pattern with  $58 \pm 2$  breaths $\cdot$ min $^{-1}$  at the highest speed, whereas at 12 and 18 km $\cdot$ h $^{-1}$  they showed diverse and individual breathing patterns of either  $57 \pm 2$  breaths $\cdot$ min $^{-1}$  ( $\sim$ 1:1 pattern) or  $32 \pm 2$  breaths $\cdot$ min $^{-1}$  ( $\sim$ 1:2 pattern), whereas a few used  $44 \pm 5$  breaths $\cdot$ min $^{-1}$  ( $\sim$ 1:1.4 pattern). At  $Pf_{80}$ , the skiers breathed  $38 \pm 4$  breaths $\cdot$ min $^{-1}$  ( $\sim$ 1:2 pattern) at the two lower speeds, changing to individually different patterns at 24 km $\cdot$ h $^{-1}$  with five skiers using  $77 \pm 3$  breaths $\cdot$ min $^{-1}$  ( $\sim$ 1:1 pattern) and four skiers taking  $44 \pm 2$  breaths $\cdot$ min $^{-1}$  ( $\sim$ 1:2 pattern). There were no differences in tidal volume between frequencies at the two lower speeds

**Table 1** Elbow joint kinematics at double poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> at submaximal treadmill speeds of 12, 18 and 24 km·h<sup>-1</sup>

Variables	km·h <sup>-1</sup>	Frequency [cycles·min <sup>-1</sup> ]			F values	Gl. Sign.	pη <sup>2</sup>	Power
		40	60	80				
EA <sub>Pole_IN</sub> [°]	12	93 ± 10 <sup>*†</sup>	75 ± 10 <sup>*</sup>	74 ± 20 <sup>†‡</sup>	$F_{(2,14)} = 26.9^a$	$P < 0.01$	0.79	1.00
	18	90 ± 6 <sup>*†</sup>	75 ± 8 <sup>*</sup>	68 ± 11 <sup>†</sup>	$F_{(2,14)} = 3.5^b$	NS		
	24	95 ± 8 <sup>*†</sup>	80 ± 9 <sup>*</sup>	76 ± 10 <sup>†</sup>	$F_{(4,28)} = 0.6^c$	NS		
EA <sub>min_PP</sub> [°]	12	70 ± 12	61 ± 10	66 ± 17	$F_{(2,14)} = 1.5^a$	NS		
	18	57 ± 13	58 ± 10	59 ± 11	$F_{(2,14)} = 11.8^b$	$P < 0.01$	0.63	0.98
	24	61 ± 10	59 ± 12	61 ± 11	$F_{(4,28)} = 1.6^c$	NS		
EA <sub>Pole_OUT</sub> [°]	12	148 ± 15 <sup>*†</sup>	102 ± 10 <sup>*‡</sup>	91 ± 12 <sup>†‡</sup>	$F_{(2,14)} = 346.2^a$	$P < 0.001$	0.98	1.00
	18	147 ± 11 <sup>*†</sup>	107 ± 8 <sup>*‡</sup>	93 ± 10 <sup>†‡</sup>	$F_{(2,14)} = 11.3^b$	$P < 0.01$	0.62	0.97
	24	157 ± 4 <sup>*†</sup>	126 ± 12 <sup>*‡</sup>	109 ± 20 <sup>†‡</sup>	$F_{(4,28)} = 1.6^c$	NS		
ROM <sub>E_FLEX</sub> [°]	12	22 ± 9 <sup>†</sup>	14 ± 5	7 ± 3 <sup>†</sup>	$F_{(2,14)} = 48.6^a$	$P < 0.001$	0.87	1.00
	18	33 ± 10 <sup>*†</sup>	17 ± 6 <sup>*‡</sup>	9 ± 2 <sup>†‡</sup>	$F_{(2,14)} = 14.0^b$	$P < 0.01$	0.67	0.93
	24	34 ± 9 <sup>*†</sup>	21 ± 8 <sup>*‡</sup>	15 ± 7 <sup>†‡</sup>	$F_{(4,28)} = 5.3^c$	$P < 0.01$	0.43	0.94
ROM <sub>E_EXT</sub> [°]	12	78 ± 16 <sup>*†</sup>	41 ± 14 <sup>*‡</sup>	25 ± 12 <sup>†‡</sup>	$F_{(2,14)} = 302.6^a$	$P < 0.001$	0.98	1.00
	18	89 ± 15 <sup>*†</sup>	48 ± 15 <sup>*‡</sup>	34 ± 16 <sup>†‡</sup>	$F_{(2,14)} = 18.9^b$	$P < 0.001$	0.73	1.00
	24	96 ± 12 <sup>*†</sup>	67 ± 15 <sup>*‡</sup>	49 ± 24 <sup>†‡</sup>	$F_{(4,28)} = 0.8^c$	NS		
AV <sub>E_FLEX</sub> [rad·s <sup>-1</sup> ]	12	2.0 ± 0.4 <sup>*†</sup>	1.4 ± 0.4 <sup>*</sup>	0.9 ± 0.4 <sup>†</sup>	$F_{(2,14)} = 61.3^a$	$P < 0.001$	0.90	1.00
	18	3.9 ± 0.9 <sup>*†</sup>	2.4 ± 0.8 <sup>*‡</sup>	1.3 ± 0.3 <sup>†‡</sup>	$F_{(2,14)} = 74.2^b$	$P < 0.001$	0.91	1.00
	24	5.2 ± 0.8 <sup>*†</sup>	3.2 ± 1.0 <sup>*</sup>	2.3 ± 1.0 <sup>†</sup>	$F_{(4,28)} = 14.3^c$	$P < 0.001$	0.67	1.00
AV <sub>E_EXT</sub> [rad·s <sup>-1</sup> ]	12	5.1 ± 1.9 <sup>†</sup>	5.4 ± 1.6 <sup>‡</sup>	4.3 ± 1.7 <sup>†‡</sup>	$F_{(2,14)} = 8.0^a$	$P < 0.01$	0.53	0.90
	18	8.2 ± 2.5 <sup>†</sup>	7.9 ± 2.4 <sup>‡</sup>	6.9 ± 2.3 <sup>†‡</sup>	$F_{(2,14)} = 29.1^b$	$P < 0.001$	0.81	1.00
	24	10.3 ± 1.6 <sup>†</sup>	10.3 ± 1.7 <sup>‡</sup>	8.6 ± 1.8 <sup>†‡</sup>	$F_{(4,28)} = 1.4^c$	NS		

$n = 9$ . Values are means ± SD. EA<sub>Pole\_IN</sub>, elbow angle at pole plant; EA<sub>min\_PP</sub>, elbow angle minimum during poling phase (PP); EA<sub>Pole\_OUT</sub>, elbow angle at the end of poling phase; ROM<sub>E\_FLEX/EXT</sub>, elbow flexion/extension range of motion during poling phase; AV<sub>E\_FLEX/EXT</sub>, average elbow flexion/extension angular velocity during poling phase. Gl. Sign., global significance; F values and Gl. Sign. determined by two-way ANOVA (3 × 3) for poling frequency (40, 60, 80 cycles·min<sup>-1</sup>) × speed (12, 18 and 24 km·h<sup>-1</sup>). pη<sup>2</sup>, partial eta square effect size

\* Difference 40–60 cycles·min<sup>-1</sup>

† Difference 40–80 cycles·min<sup>-1</sup>

‡ Difference 60–80 cycles·min<sup>-1</sup>;  $P < 0.05$

<sup>a</sup> Main effect frequency

<sup>b</sup> Main effect speed

<sup>c</sup> Interactive effect (frequency × speed)

(12 km·h<sup>-1</sup>: 1.36–1.48 L; 18 km·h<sup>-1</sup>: 1.86–1.97 L). At 24 km·h<sup>-1</sup> skiers had a higher tidal volume at Pf<sub>40</sub> (2.61 ± 0.23 L) versus Pf<sub>60</sub> & 80 (2.11 ± 0.26 L; 2.20 ± 0.28 L) (all  $P < 0.05$ ), thereby showing a frequency-speed interaction effect ( $F_{(4,28)} = 5.5$ ,  $P < 0.01$ ; pη<sup>2</sup> = 0.44; Power = 0.95).

#### Work rate, metabolic rate and efficiency at different poling frequencies

External work rate was 111 ± 9, 166 ± 14 and 222 ± 18 W at 12, 18 and 24 km·h<sup>-1</sup>, respectively for all frequencies, showing a main effect of speed ( $F_{(2,14)} = 1358$ ,  $P < 0.001$ ). Metabolic rate was 8–15% lower at Pf<sub>40</sub> & 60 versus Pf<sub>80</sub> at all speeds ( $P < 0.05$ )

without frequency-speed interaction ( $F_{(4,28)} = 3.0$ ,  $P > 0.05$ ) (Fig. 6a). Gross efficiency decreased from Pf<sub>40</sub> to Pf<sub>60</sub> and declined further for Pf<sub>80</sub> at 12 and 18 km·h<sup>-1</sup> (all  $P < 0.05$ ), but was higher for Pf<sub>40</sub> & 60 versus Pf<sub>80</sub> at 24 km·h<sup>-1</sup> ( $P < 0.05$ ). Global differences between speeds ( $F_{(2,14)} = 17.4$ ,  $P < 0.001$ ) could be detected, but no frequency-speed interaction was observed ( $F_{(4,28)} = 1.3$ ,  $P > 0.05$ ) (Fig. 6b).

#### Discussion

The main findings of the present study comparing low versus medium versus high poling frequencies (Pf<sub>40</sub> vs. Pf<sub>60</sub> vs. Pf<sub>80</sub>) at three submaximal speeds were as follows:



**Table 2** Hip joint kinematics at double poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> at submaximal treadmill speeds of 12, 18 and 24 km·h<sup>-1</sup>

Variables	km·h <sup>-1</sup>	Frequency [cycles·min <sup>-1</sup> ]			<i>F</i> values	Gl. Sign.	<i>pη</i> <sup>2</sup>	Power
		40	60	80				
HA <sub>Pole_IN</sub> [°]	12	155 ± 7 <sup>†</sup>	150 ± 7	148 ± 8 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 4.5 <sup>a</sup>	<i>P</i> < 0.05	0.39	0.66
	18	149 ± 7 <sup>*</sup>	142 ± 6 <sup>*</sup>	143 ± 9	<i>F</i> <sub>(2,14)</sub> = 43.1 <sup>b</sup>	<i>P</i> < 0.001	0.86	1.00
	24	136 ± 7	137 ± 11	135 ± 12	<i>F</i> <sub>(4,28)</sub> = 8.8 <sup>c</sup>	<i>P</i> < 0.01	0.56	0.94
HA <sub>min_PP</sub> [°]	12	121 ± 6 <sup>†</sup>	123 ± 8	129 ± 9 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 12.4 <sup>a</sup>	<i>P</i> < 0.01	0.64	0.86
	18	115 ± 6 <sup>†</sup>	118 ± 6	122 ± 7 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 21.8 <sup>b</sup>	<i>P</i> < 0.01	0.76	0.99
	24	106 ± 10 <sup>†</sup>	111 ± 9	113 ± 10 <sup>†</sup>	<i>F</i> <sub>(4,28)</sub> = 1.03 <sup>c</sup>	NS		
HA <sub>Pole_OUT</sub> [°]	12	124 ± 8 <sup>†</sup>	127 ± 11	130 ± 9 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 10.0 <sup>a</sup>	<i>P</i> < 0.05	0.59	0.84
	18	116 ± 7 <sup>†</sup>	119 ± 7	122 ± 8 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 17.9 <sup>b</sup>	<i>P</i> < 0.01	0.72	0.96
	24	109 ± 9 <sup>†</sup>	112 ± 9	115 ± 10 <sup>†</sup>	<i>F</i> <sub>(4,28)</sub> = 1.05 <sup>c</sup>	NS		
HA <sub>max_RP</sub> [°]	12	179 ± 8 <sup>*†</sup>	170 ± 7 <sup>*‡</sup>	161 ± 7 <sup>‡</sup>	<i>F</i> <sub>(2,14)</sub> = 50.5 <sup>a</sup>	<i>P</i> < 0.001	0.88	1.00
	18	183 ± 10 <sup>*†</sup>	174 ± 9 <sup>*‡</sup>	165 ± 7 <sup>‡</sup>	<i>F</i> <sub>(2,14)</sub> = 7.6 <sup>b</sup>	<i>P</i> < 0.05	0.52	0.70
	24	184 ± 12 <sup>*†</sup>	175 ± 10 <sup>*‡</sup>	164 ± 8 <sup>‡</sup>	<i>F</i> <sub>(4,28)</sub> = 0.29 <sup>c</sup>	NS		
ROM <sub>H_FLEX/EXT</sub> [°]	12	58 ± 5 <sup>*†</sup>	47 ± 8 <sup>*‡</sup>	32 ± 7 <sup>‡</sup>	<i>F</i> <sub>(2,14)</sub> = 116.6 <sup>a</sup>	<i>P</i> < 0.001	0.94	0.98
	18	69 ± 14 <sup>*†</sup>	56 ± 11 <sup>*‡</sup>	43 ± 9 <sup>‡</sup>	<i>F</i> <sub>(2,14)</sub> = 20.8 <sup>b</sup>	<i>P</i> < 0.01	0.75	0.70
	24	78 ± 18 <sup>*†</sup>	64 ± 15 <sup>*‡</sup>	51 ± 14 <sup>‡</sup>	<i>F</i> <sub>(4,28)</sub> = 0.38 <sup>c</sup>	NS		
ROM <sub>H_FLEX/EXT</sub> [°·min <sup>-1</sup> ]	12	4640 ± 394 <sup>*†</sup>	5640 ± 992 <sup>*</sup>	5120 ± 1058 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 24.0 <sup>a</sup>	<i>P</i> < 0.01	0.77	0.99
	18	5520 ± 1114 <sup>*†</sup>	6720 ± 1340 <sup>*</sup>	6880 ± 1389 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 20.7 <sup>b</sup>	<i>P</i> < 0.01	0.75	0.98
	24	6240 ± 1408 <sup>*†</sup>	7680 ± 1825 <sup>*</sup>	8160 ± 2228 <sup>†</sup>	<i>F</i> <sub>(4,28)</sub> = 6.3 <sup>c</sup>	<i>P</i> < 0.01	0.47	0.97
AV <sub>H_FLEX</sub> [rad·s <sup>-1</sup> ]	12	1.5 ± 0.2 <sup>*</sup>	1.9 ± 0.4 <sup>*</sup>	1.6 ± 0.4	<i>F</i> <sub>(2,14)</sub> = 7.0 <sup>a</sup>	<i>P</i> < 0.05	0.50	0.68
	18	1.9 ± 0.5	2.1 ± 0.4	2.1 ± 0.4	<i>F</i> <sub>(2,14)</sub> = 22.3 <sup>b</sup>	<i>P</i> < 0.01	0.76	0.99
	24	2.3 ± 0.5 <sup>*</sup>	2.5 ± 0.5 <sup>*</sup>	2.7 ± 0.7	<i>F</i> <sub>(4,28)</sub> = 4.3 <sup>c</sup>	<i>P</i> < 0.01	0.38	0.88
AV <sub>H_EXT</sub> [rad·s <sup>-1</sup> ]	12	1.4 ± 0.2 <sup>*</sup>	1.8 ± 0.4 <sup>*</sup>	1.7 ± 0.5	<i>F</i> <sub>(2,14)</sub> = 21.2 <sup>a</sup>	<i>P</i> < 0.01	0.75	0.98
	18	1.6 ± 0.3 <sup>*†</sup>	2.2 ± 0.6 <sup>*</sup>	2.3 ± 0.7 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 20.5 <sup>b</sup>	<i>P</i> < 0.01	0.75	0.98
	24	1.7 ± 0.4 <sup>*†</sup>	2.5 ± 0.7 <sup>*</sup>	2.6 ± 0.8 <sup>†</sup>	<i>F</i> <sub>(4,28)</sub> = 12.4 <sup>c</sup>	<i>P</i> < 0.001	0.64	1.00

*n* = 9. Values are means ± SD. HA<sub>Pole\_IN</sub>, hip angle at pole plant; HA<sub>min\_PP</sub>, hip angle minimum during poling phase; HA<sub>Pole\_OUT</sub>, hip angle at the end of poling phase; HA<sub>max\_RP</sub>, hip angle maximum during recovery phase; ROM<sub>H\_FLEX/EXT</sub>, hip flexion/extension range of motion during double poling cycle; AV<sub>H\_FLEX/EXT</sub>, average hip flexion/extension angular velocity during double poling cycle; Gl. Sign., global significance; *F* values and Gl. Sign. determined by two-way ANOVA (3 × 3) for poling frequency (40, 60, 80 cycles·min<sup>-1</sup>) × speed (12, 18 and 24 km·h<sup>-1</sup>). *pη*<sup>2</sup>, partial eta square effect size

\* Difference 40–60 cycles·min<sup>-1</sup>

† Difference 40–80 cycles·min<sup>-1</sup>

‡ Difference 60–80 cycles·min<sup>-1</sup>; *P* < 0.05

<sup>a</sup> Main effect frequency

<sup>b</sup> Main effect speed

<sup>c</sup> Interactive effect (frequency × speed)

(1) Absolute poling and recovery time decreased at all speeds, with shorter relative poling and longer relative recovery times at low versus high frequencies; (2) peak pole force, time to peak and impulse of force decreased, but impact pole force and rate of force development increased with higher frequency at nearly all speeds; (3) elbow joint ranges of motion and angular velocities decreased at all speeds; (4) hip and knee joints showed greater maxima, smaller minima and greater ranges of motion within one cycle, but smaller flexion/extension ranges of motion per

minute at nearly all speeds; (5) oxygen uptake and heart rate were lower at the two lower frequencies; (6) blood lactate concentration was second lowest at Pf<sub>40</sub>, lowest at Pf<sub>60</sub> and highest at Pf<sub>80</sub>, showing a J-shape curve with increasing frequency but only at the highest speed; (7) gross efficiency decreased with higher frequencies at the two lower speeds and was higher for the two lower frequencies at the highest speed; (8) pulmonary ventilation was lower at Pf<sub>40</sub> versus Pf<sub>80</sub> with the largest and gradual increases at the highest speed.

**Table 3** Knee joint kinematics at double poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> at submaximal treadmill speeds of 12, 18 and 24 km·h<sup>-1</sup>

Variables	km·h <sup>-1</sup>	Frequency [cycles·min <sup>-1</sup> ]			<i>F</i> values	Gl. Sign.	<i>p</i> η <sup>2</sup>	Power
		40	60	80				
KA <sub>Pole_IN</sub> [°]	12	163 ± 6 <sup>†</sup>	160 ± 4	158 ± 5 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 6.0 <sup>a</sup>	<i>P</i> < 0.05	0.46,	0.62
	18	160 ± 4 <sup>†</sup>	155 ± 5	154 ± 6 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 56.2 <sup>b</sup>	<i>P</i> < 0.001	0.89	1.00
	24	151 ± 4 <sup>†</sup>	150 ± 5	145 ± 6 <sup>†</sup>	<i>F</i> <sub>(4,28)</sub> = 2.4 <sup>c</sup>	NS		
KA <sub>min_PP</sub> [°]	12	150 ± 8	150 ± 5	151 ± 6	<i>F</i> <sub>(2,14)</sub> = 11.5 <sup>a</sup>	<i>P</i> < 0.01	0.62	0.98
	18	138 ± 6 <sup>*†</sup>	144 ± 6 <sup>*</sup>	145 ± 7 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 66.7 <sup>b</sup>	<i>P</i> < 0.001	0.91	1.00
	24	129 ± 5 <sup>*†</sup>	135 ± 6 <sup>*</sup>	136 ± 7 <sup>†</sup>	<i>F</i> <sub>(4,28)</sub> = 5.3 <sup>c</sup>	<i>P</i> < 0.05	0.43	0.77
KA <sub>Pole_OUT</sub> [°]	12	153 ± 5	153 ± 9	153 ± 6	<i>F</i> <sub>(2,14)</sub> = 1.1 <sup>a</sup>	NS		
	18	144 ± 5	145 ± 6	146 ± 7	<i>F</i> <sub>(2,14)</sub> = 81.5 <sup>b</sup>	<i>P</i> < 0.001	0.92	1.00
	24	135 ± 7	136 ± 5	138 ± 6	<i>F</i> <sub>(4,28)</sub> = 2.5 <sup>c</sup>	NS		
KA <sub>max_RP</sub> [°]	12	171 ± 4 <sup>†</sup>	167 ± 5	165 ± 4 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 20.6 <sup>a</sup>	<i>P</i> < 0.001	0.75	1.00
	18	172 ± 5 <sup>†</sup>	168 ± 5	166 ± 5 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 1.3 <sup>b</sup>	NS		
	24	173 ± 5 <sup>†</sup>	168 ± 4	164 ± 6 <sup>†</sup>	<i>F</i> <sub>(4,28)</sub> = 0.31 <sup>c</sup>	NS		
ROM <sub>K_FLEX/EXT</sub> [°]	12	21 ± 6 <sup>*†</sup>	17 ± 5 <sup>*</sup>	14 ± 4 <sup>†</sup>	<i>F</i> <sub>(2,14)</sub> = 21.8 <sup>a</sup>	<i>P</i> < 0.001	0.76	1.00
	18	31 ± 6 <sup>*†</sup>	24 ± 6 <sup>*‡</sup>	20 ± 5 <sup>†‡</sup>	<i>F</i> <sub>(2,14)</sub> = 41.1 <sup>b</sup>	<i>P</i> < 0.001	0.85	1.00
	24	43 ± 9 <sup>*†</sup>	33 ± 8 <sup>*‡</sup>	28 ± 8 <sup>†‡</sup>	<i>F</i> <sub>(4,28)</sub> = 4.4 <sup>c</sup>	<i>P</i> < 0.01	0.38	0.87
ROM <sub>K_FLEX/EXT</sub> [°·min <sup>-1</sup> ]	12	1680 ± 111 <sup>*†</sup>	2040 ± 341 <sup>*‡</sup>	2240 ± 497 <sup>†‡</sup>	<i>F</i> <sub>(2,14)</sub> = 27.7 <sup>a</sup>	<i>P</i> < 0.001	0.80	1.00
	18	2480 ± 407 <sup>*†</sup>	2880 ± 661 <sup>*‡</sup>	3200 ± 779 <sup>†‡</sup>	<i>F</i> <sub>(2,14)</sub> = 38.6 <sup>b</sup>	<i>P</i> < 0.001	0.85	1.00
	24	3440 ± 544 <sup>*†</sup>	3960 ± 843 <sup>*‡</sup>	4480 ± 1217 <sup>†‡</sup>	<i>F</i> <sub>(4,28)</sub> = 2.2 <sup>c</sup>	NS		
AV <sub>K_FLEX</sub> [rad·s <sup>-1</sup> ]	12	0.9 ± 0.1	1.1 ± 0.3	1.0 ± 0.2	<i>F</i> <sub>(2,14)</sub> = 2.5 <sup>a</sup>	NS		
	18	1.4 ± 0.2	1.6 ± 0.4	1.5 ± 0.3	<i>F</i> <sub>(2,14)</sub> = 105.3 <sup>b</sup>	<i>P</i> < 0.001	0.94	1.00
	24	1.9 ± 0.4	2.0 ± 0.3	2.1 ± 0.4	<i>F</i> <sub>(4,28)</sub> = 0.67 <sup>c</sup>	NS		
AV <sub>K_EXT</sub> [rad·s <sup>-1</sup> ]	12	0.4 ± 0.2 <sup>*†</sup>	0.5 ± 0.1 <sup>*†</sup>	0.7 ± 0.2 <sup>†‡</sup>	<i>F</i> <sub>(2,14)</sub> = 43.0 <sup>a</sup>	<i>P</i> < 0.001	0.86	1.00
	18	0.5 ± 0.1 <sup>*†</sup>	0.8 ± 0.1 <sup>*‡</sup>	1.0 ± 0.3 <sup>*‡</sup>	<i>F</i> <sub>(2,14)</sub> = 42.5 <sup>b</sup>	<i>P</i> < 0.001	0.86	1.00
	24	0.8 ± 0.1 <sup>*†</sup>	1.1 ± 0.2 <sup>*</sup>	1.4 ± 0.3 <sup>†</sup>	<i>F</i> <sub>(4,28)</sub> = 3.4 <sup>c</sup>	<i>P</i> < 0.05	0.33	0.79

*n* = 9. Values are means ± SD. KA<sub>Pole\_IN</sub>, knee angle at pole plant; KA<sub>min\_PP</sub>, knee angle minimum during poling phase; KA<sub>Pole\_OUT</sub>, knee angle at the end of poling phase; KA<sub>max\_RP</sub>, knee angle maximum during recovery phase; ROM<sub>K\_FLEX/EXT</sub>, knee flexion/extension range of motion during double poling cycle; AV<sub>K\_FLEX/EXT</sub>, average knee flexion/extension angular velocity during double poling cycle. Gl. Sign., global significance; *F* values and Gl. Sign. determined by two-way ANOVA (3 × 3) for poling frequency (40, 60, 80 cycles·min<sup>-1</sup>) × speed (12, 18 and 24 km·h<sup>-1</sup>). *p*η<sup>2</sup>, partial eta square effect size

\* Difference 40–60 cycles·min<sup>-1</sup>

† Difference 40–80 cycles·min<sup>-1</sup>

‡ Difference 60–80 cycles·min<sup>-1</sup>; *P* < 0.05

<sup>a</sup> Main effect frequency

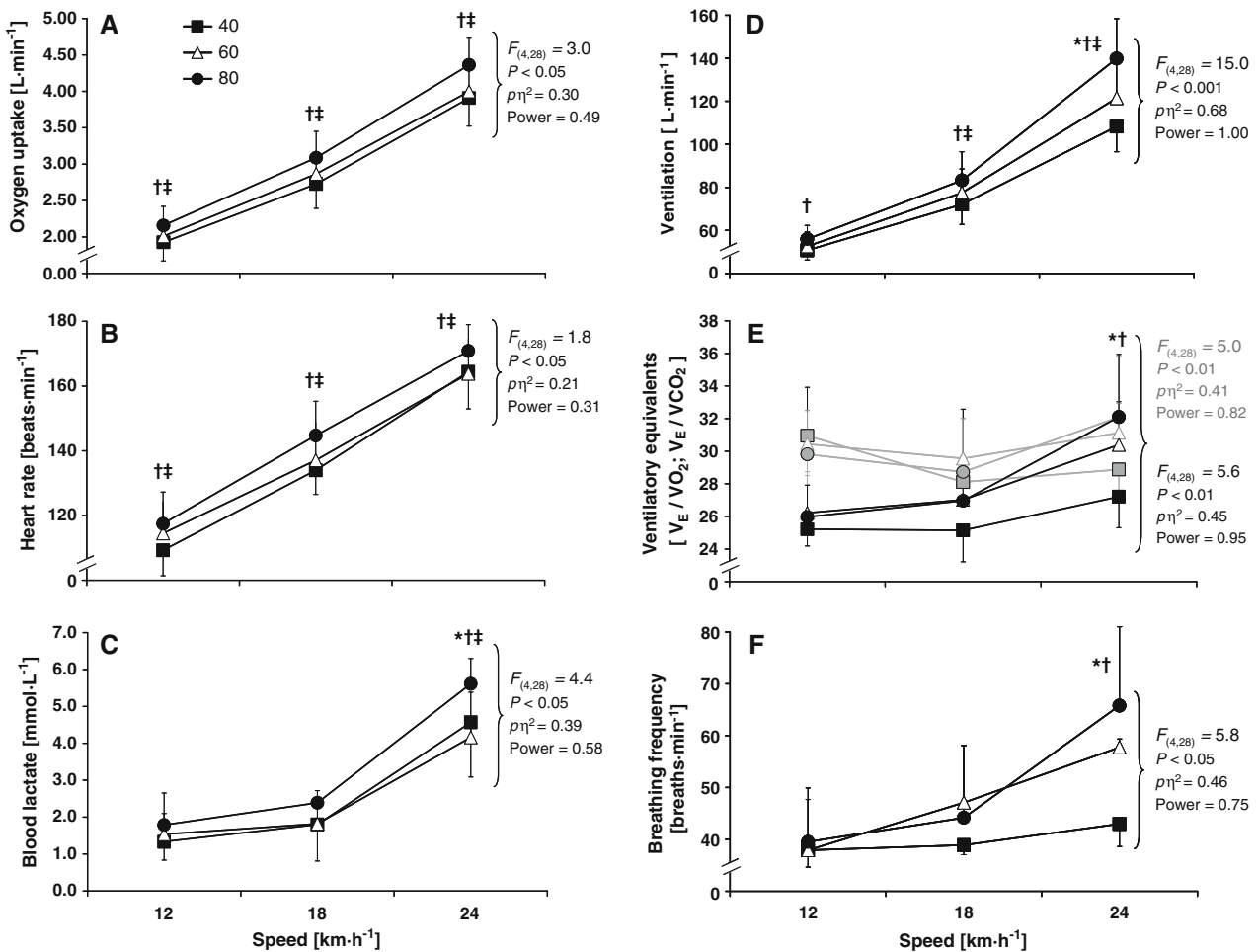
<sup>b</sup> Main effect speed

<sup>c</sup> Interactive effect (frequency × speed)

### Cycle and pole force characteristics

Double poling speed is governed by the product of generated distance per cycle (cycle length) and poling frequency. The fixed frequencies and submaximal speeds in the current study assess the cycle length to be the crucial factor that has to be managed during these different situations. Thus, the skiers were challenged to generate either relatively short cycle lengths at the highest analysed frequency (2.5–5 m), or twofold longer cycle lengths of up to ~ 10 m at the lowest frequency and the highest speed

(Fig. 1a), a value which is to date the greatest reported among top-elite skiers using the double poling technique. It is important to mention that the ability to create longer gliding distances per cycle at lower or similar cycle rates during different techniques has been described as one of the main factors to discriminate between faster and slower cross-country skiers (Bilodeau et al. 1996; Dillman 1979; Ekström 1980; Holmberg et al. 2005, 2006; Lindinger et al. 2009a; Smith 2002; Stoeggel et al. 2007; Stöggl and Müller 2009). As regards double poling, better performance coupled with longer cycle length and lower poling frequency



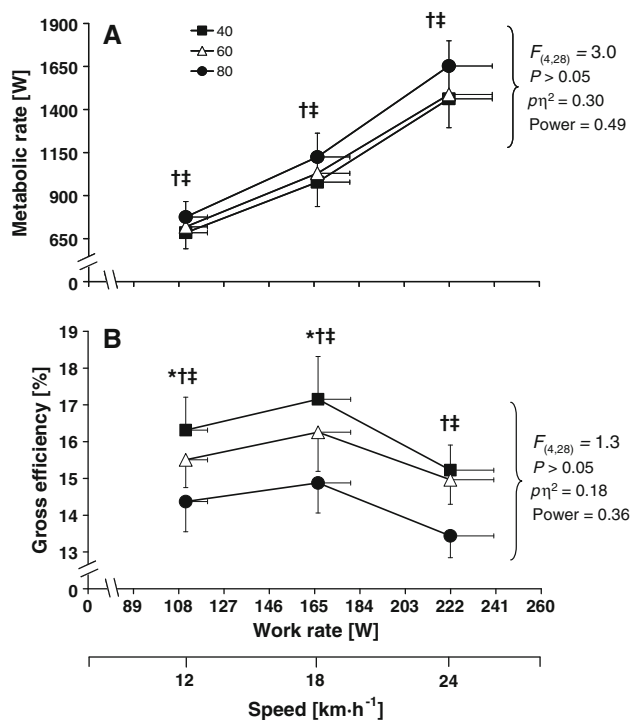
**Fig. 5** Oxygen uptake (a), heart rate (b), blood lactate (c), pulmonary ventilation (d), ventilatory equivalents for oxygen (V<sub>E</sub>/V<sub>O<sub>2</sub></sub>) and carbon dioxide (V<sub>E</sub>/V<sub>CO<sub>2</sub></sub>) (e) and breathing frequency (f) at poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> at submaximal treadmill speeds of 12, 18 and 24 km·h<sup>-1</sup>. The data are mean ± SD (n = 9).

F values, P values, partial eta square effect size (pη<sup>2</sup>) and power are presented for two-way ANOVA (frequency \* speed). \*Difference 40–60 cycles·min<sup>-1</sup>; †Difference 40–80 cycles·min<sup>-1</sup>; ‡Difference 60–80 cycles·min<sup>-1</sup>. P < 0.05

was related to a new technical pattern (Holmberg et al. 2005, 2006). This was characterized by shorter push-offs with higher forces, generated by a more pronounced flexion and extension in the arm and leg joints. Such a fundamental pattern has recently also been found to be related to higher diagonal skiing performance (Lindinger et al. 2009a). However, it is probably not a question of maximizing cycle length, but rather of finding an optimal relationship between cycle length and poling frequency or impulse of force and available poling time, especially at higher skiing speeds (Stöggl and Müller 2009). So the question arose: What are the biomechanical consequences, limits and benefits when double poling at low to high frequencies with long to short cycle lengths at different submaximal speeds?

The longer cycle lengths at lower poling frequencies in the current study were attained by up to ~ 38% higher impulses of pole force, mainly due to the distinctly longer

poling times at all speeds during which skiers could transfer force to the ground (Fig. 1a, b). At the higher speeds, the impulse of pole force was additionally generated by higher peak pole forces presumably from the recruitment of more fast-twitch motor units (Figs. 2b, f, 3). Therefore, low poling frequency training performed at higher submaximal speeds could be beneficial as ski-specific strength training. The absolute poling time may be a critical factor as regards the efficient transfer of force to the ground and thereby creating forward propulsion and speed. Double poling at 24 km·h<sup>-1</sup> at the low frequency of Pf<sub>40</sub> required the highest impulse of force (44 ± 5 Ns) which was created during a rather limited but still longer and optimally short poling time of 0.28 ± 0.02 s (Figs. 1b, 3). This situation undoubtedly challenges both high power capabilities and sophisticated technical skills, especially at high speeds (Holmberg et al. 2005). Poling times <0.28 s have been discussed as getting critical lower limits in



**Fig. 6** Metabolic rate (a) and gross efficiency (b) at poling frequencies of 40, 60 and 80 cycles·min<sup>-1</sup> plotted against work rates at submaximal treadmill speeds of 12, 18 and 24 km·h<sup>-1</sup>. The data are mean  $\pm$  SD ( $n = 9$ ).  $F$  values,  $P$  values, partial eta square effect size ( $\rho\eta^2$ ) and power are presented for two-way ANOVA (frequency \* speed). \*Difference 40–60 cycles·min<sup>-1</sup>; †Difference 40–80 cycles·min<sup>-1</sup>; ‡Difference 60–80 cycles·min<sup>-1</sup>.  $P < 0.05$

double poling for the full recruitment of different muscle fibres for a sufficient force generation at high to maximal speeds (Lindinger et al. 2009b, c). The maintenance of the longest possible ground contact time can be considered as relevant in all forms of human locomotion with the constraints of stopping the foot, arm or pole with respect to the ground (Minetti 2004), in particular at higher speeds. Considering this aspect, double poling frequencies of  $\sim 80$  cycles·min<sup>-1</sup> can be assessed as unfavourable due to several interrelated aspects: (1) Poling times were substantially below critical limits with 0.25–0.19 s (12–24 km·h<sup>-1</sup>). (2) Times to peak pole force, corresponding to available times for eccentric force generation (Holmberg et al. 2005; Lindinger et al. 2009b, c), reached values of  $< 0.06$  s at the highest speed, leading to up to 107% higher rates of force development. Early studies on force–velocity characteristics regarding contraction velocity on single fibres in vivo demonstrated that Type I fibres need  $\sim 100$ – $140$  ms and Type IIA fibres  $\sim 55$ – $85$  ms to create maximal tension and thereby force (Buchthal and Schmalbruch 1970; Eberstein and Goodgold 1968; Garnett et al. 1978); thus, due to mentioned lower time values, a high frequency of Pf<sub>80</sub> can be considered as causing a less efficient force development compared to lower frequencies.

It can be argued that low poling frequencies enable skiers to “defend” a certain minimum of poling time even at high speeds, in order to generate pole force more efficiently through the recruitment of a larger amount of different muscle fibre types. Elite skiers’ strategy to optimize pole ground contact time can be associated with their ability to maintain the poling frequency as low as possible, also at high speeds, and their technical approach to gain longer covered distance of the pole along the ground during the pole thrust. This could be accomplished through two main factors (Stöggl and Müller 2009): (1) Pole plant at greater angles with respect to the ground up to 90°, possibly also creating a better preloading of the upper body extensor muscles and higher strain energy in the poles. (2) A greater forward lean for the entire body and a higher position for the centre of mass, which is partly confirmed by our data with the greater hip and knee angle maxima, observed shortly before pole plant at the lowest poling frequency (Tables 2, 3). To avoid muscular limitations of force production at too short ground contacts, Minetti (2004) suggested developing a new pole tip design that allows the end of the pole to slide, a passive tool comparable with skating skis where skiers perform the leg push-off from the gliding ski. The influence of pole angle at different poling frequencies and speeds needs to be further investigated in future studies using 3D kinematics.

Absolute recovery time was found to be distinctly shorter at Pf<sub>80</sub> and Pf<sub>60</sub> than at Pf<sub>40</sub> (Fig. 1c). Additionally, the relative recovery and poling times were longer and shorter, respectively, at the lowest versus the two higher frequencies, particularly at the highest submaximal speed (Fig. 1d). A longer recovery time provides more time to reposition the skiers up to their starting “high hip-high heel” position (Holmberg et al. 2005), which was characterized by greater maximal hip and knee angles at lower poling frequencies, occurring shortly before the subsequent pole plant (Tables 2, 3; Fig. 4b, c). The longer recovery times, combined with lower poling frequencies, have been reported as important characteristics of high double poling performance in elite skiers (Holmberg et al. 2005) and were related to a longer time to exhaustion (Holmberg et al. 2006). These findings are similar to poling during V2-alternate ski skating (Millet et al. 1998a) and to other sports like, i.e. wheelchair racing (Van der Woude et al. 1989), where increasing cycle rates were associated primarily with a decrease in recovery times. Thus, from the perspective of percentage distribution between the poling and recovery phase within one cycle, low frequencies can be considered to be more beneficial and less exhausting compared to higher frequencies.

With special focus on the pole force curves generated using different poling frequencies at different speeds, diverse patterns could be found (Fig. 3). Interestingly, the

impact force was highest at  $Pf_{80}$  and lowest at  $Pf_{40}$ , whereas the peak pole force showed the opposite pattern, leading to greater impact force-to-peak pole force ratios of nearly 1 (0.81–0.94) at the highest frequency at all speeds (Fig. 2c), along with the later occurrence of peak force at  $Pf_{40}$  at all speeds, resulting in a lower rate of force development (Fig. 2d, e).

We suggest that the  $\sim 40\%$  higher impact force at  $Pf_{80}$  is caused by the distinctly shortened recovery phase (Fig. 1c) with lower values of 0.49–0.56 s, which is less than half compared to  $Pf_{40}$  at all speeds, causing a stressed body repositioning and a less controlled forward movement of the poles and pole plant (Figs. 2a, 3) which was observed in some skiers at the highest frequency. This situation may create difficulties in coordinatively handle the poles' angle to the ground at pole plant and consequently negatively influences pole force dynamics. Hence, we propose that there may be an upper frequency threshold at high speeds above which skiers have difficulties to effectively generate force.

#### Joint kinematics

Elbow flexion and extension ranges of motion were  $\sim 50\text{--}70\%$  larger at  $Pf_{40}$  compared to  $Pf_{80}$ , with gradual reductions in ranges of motion at most submaximal speeds, due to greater elbow angles at pole plant and the end of pole ground contact (Table 1; Fig. 4a). Mainly due to these changes, elbow flexion and extension angular velocities were greater at low compared to high poling frequencies, reaching  $5.2 \pm 0.8 \text{ rad}\cdot\text{s}^{-1}$  and  $10.3 \pm 1.6 \text{ rad}\cdot\text{s}^{-1}$  at the highest speed. This pronounced pattern in the elbow joint, especially at the lowest frequency and highest speed, can be explained by the necessity of generating the highest forces, in order to gain cycle lengths up to  $\sim 10$  m. Distinct stretch–shortening cycles in the elbow and shoulder joints have previously been reported as a function of increasing speed up to individual maxima (Lindinger et al. 2009b, c) and as an important characteristic of double poling performance (Holmberg et al. 2005). Interestingly, also in diagonal skiing a dynamic, short flexion pattern in the leg joints has been described as an essential part of a stretch–shortening cycle, preloading the extensor muscles for an efficient transmission of muscular force to the ground during leg thrust (Komi and Norman 1987; Lindinger et al. 2009a; Vähäsöyrinki et al. 2008). Similar to the effects of speed (Lindinger et al. 2009b, c), the decrease in poling frequency increases the possibility for an effective stretch–shortening cycle with (1) increased angular elbow flexion (muscle–tendon stretch) velocities, (2) a more immediate transition from flexion to extension phase and (3) the increased forces during the flexion phase (Komi 2000). These characteristics have been shown to be responsible

for a distinct increase in triceps brachii muscle activity during elbow flexion and a decreased electromyographic (EMG) activity from the flexion to extension phase (Lindinger et al. 2009b). High EMG activity and stretching velocities of the muscle–tendon complex during flexion have been reported to create higher muscle stiffness and better conditions for the storage of elastic strain energy (Bosco et al. 1981; Gollhofer et al. 1984; Ishikawa and Komi 2004; Komi and Gollhofer 1997; Kuitunen et al. 2002). Consequently, the lower motor unit activity during the concentric phase in the triceps muscle during double poling (Lindinger et al. 2009b), as well as in the leg muscles during diagonal skiing (Komi and Norman 1987), has been interpreted as increased mechanical efficiency and thereby economized human locomotion (Cavagna et al. 1964) by lower expenditure of metabolic energy in the muscle (Norman and Komi 1985). How frequency in detail influences the stretch–shortening cycle muscle activity during double poling needs to be further investigated.

Similar to the changes of the elbow joint patterns, hip and knee joints also showed greater flexion/extension ranges of motion at low versus high poling frequencies (Tables 2, 3; Fig. 4b, c). At the two lower frequencies, the skiers started from a more extended hip and knee joint position shortly before pole plant, reached smaller angle minima (more flexion) during the poling phase only at higher speeds and thereafter repositioned their body back up to the “higher” posture again. In earlier studies, the positive role and importance of more pronounced lower body actions during double poling has been reported as regards higher peak and impulses of pole force (Holmberg et al. 2005, 2006; Lindinger et al. 2009c) and higher double poling performance. These findings can be confirmed by the current study, as the skiers were challenged to create higher forces at low frequencies, in particular at  $24 \text{ km}\cdot\text{h}^{-1}$ , in order to support upper body work and gain higher forces and thereby longer cycle lengths of up to 10 m.

#### Physiological response

##### *Oxygen cost and heart rate*

The 8–13% lower oxygen cost and the 3–8% lower heart rate at all speeds at  $Pf_{40}$  &  $60$  versus  $Pf_{80}$  are suggested to be (1) mainly explained by differences in internal work and to a lesser extent by (2) the increased pulmonary ventilation and (3) the presumably differences in muscle activation.

The oxygen cost for the internal work of moving the body up and down during each cycle is of special concern in double poling, where athletes have the possibility to freely adjust the flexion/extension ranges of motion in hip and knee joints when using different frequencies. This is a

fundamental difference to cycling, for example, which represents a closed-chain exercise with limited possibilities to adapt leg joint kinematics to different frequencies. The internal work during each double poling cycle has been reported as representing nearly 30% of the total energy cost (Holmberg 2005), a high value that can be explained by two factors: The skier's body, in particular upper body representing ~70% of body mass (Piriyaarasarth et al. 2008; Winter 1990), has to be repetitively (1) decelerated eccentrically during the poling phase by the involved joint extensor muscles when reaching the low crunched double poling position and (2) repositioned during recovery phase back up to the skier's so called "high hip-high heel" position at the end of each cycle to be prepared for the next pole plant (Holmberg et al. 2005, 2006). So why can this typical and extensive internal work be considered to be greater at high compared to low double poling frequencies and thereby result in a higher energy cost? Two explanations are suggested: (1) The hip and knee flexion/extension ranges of motion, summed over 1 min, were up to 33% greater at the highest frequency compared to lower ones (Tables 2, 3), although the ranges of motion during a single double poling cycle were greater at the lowest frequency. (2) Up to 54% shorter recovery times at the highest frequency provided distinctly less time to reposition the body for the subsequent pole plant, leading up to 51 and 91% greater angular hip and knee extension velocities, respectively, especially at the highest speed. In contrast, the eccentric work (hip and knee flexion), characterizing the transition from the recovery to the poling phase, was performed at similar angular flexion velocities at all frequencies at all speeds.

A second explanation for differences in oxygen cost could be that the increased poling frequency contributed to a gradually and up to 29% higher pulmonary ventilation (Fig. 5d) and thereby higher oxygen cost (Fig. 5a), especially at higher speeds. It is noteworthy that all skiers showed a 1:1 locomotor-respiratory coupling pattern at Pf<sub>40</sub> but the patterns at Pf<sub>60</sub> and Pf<sub>80</sub> were different. At Pf<sub>60</sub> the skiers breathed below their given poling frequency at the two lower speeds, thereafter approaching 1:1 at the highest speed, whereas Pf<sub>80</sub> showed a diverse pattern where the skiers were either breathing at approximately every two or at every poling cycle, the latter pattern getting more used at the highest speed (Fig. 5f). Thus, skiers may have limited their breathing frequency at Pf<sub>60</sub> and Pf<sub>80</sub> at lower speeds in order to save energy, as the cost of breathing per se has been reported to be ~5–10% of the pulmonary oxygen uptake (Aaron et al. 1992; Bartlett et al. 1958; Coast et al. 1993; Manohar 1987; Margaria et al. 1960; McKerrow and Otis 1956).

Finally, a third aspect that may have contributed to lower oxygen cost at the lower frequencies is an altered

kind of extensor muscle activation characterized by a more pronounced stretch–shortening cycle pattern in the elbow joint (Fig. 4a; Table 1), previously reported to be mainly an effect of increasing speed on elbow and shoulder joint kinematics and thereby on upper body extensor muscle activation in double poling (Lindinger et al. 2009b). Thus, it can be speculated that a low poling frequency with a more than twofold higher angular elbow flexion velocity and range of motion (Table 1) may cause a higher pre-stretch velocity of the muscle–tendon complex, hence lead to stiffer muscle fascicles and increased tendinous tissue lengthening (Ishikawa and Komi 2008; Magnusson et al. 2008) and thereby enhance the generation of elastic strain energy (Bosco et al. 1982; Komi and Gollhofer 1997). This can be utilized during the subsequent pole thrust and enables higher muscle outputs and forces despite a decreased concentric motor unit activity in elbow and shoulder extensors (neural input) (Lindinger et al. 2009b) which has been described to lower the expenditure of metabolic energy in the muscles and thereby improve the economy of human locomotion (Cavagna et al. 1964; Komi and Norman 1987; Norman and Komi 1985). This possible increased mechanical efficiency during more pronounced stretch–shortening cycles when poling at rather low versus high frequencies especially at higher speeds may partly and additionally explain the lower oxygen cost and heart rate found in the current study (Fig. 5a, b).

#### *Metabolic response*

The most pronounced lactate response at the highest frequency of Pf<sub>80</sub>, the second lowest at Pf<sub>40</sub> and the lowest at Pf<sub>60</sub>, overall showing a J-curve at the highest speed, may be explained by different factors. We suggest that the second highest lactate response at Pf<sub>40</sub> is due to ~25% higher peak pole forces at the highest speed compared to Pf<sub>60</sub> and Pf<sub>80</sub>. This implies a higher relative muscular load, especially on the upper body muscles used for propulsion (Holmberg et al. 2005; Lindinger et al. 2009b) to reach the fairly long cycle lengths of ~10 m, and the arms known to produce more lactate than the legs at a given submaximal workload (Ahlborg and Jensen-Urstad 1991). Furthermore, we suggest that the higher lactate response at Pf<sub>80</sub> was influenced by the distinctly shorter (37–55%) absolute but also relative recovery time at the highest movement frequency compared Pf<sub>60</sub> and Pf<sub>40</sub>, respectively, because blood flow to exercising muscles occurs during the relaxation phases between muscle contractions (Radegran and Saltin 1998). So why was the lactate concentration lower at Pf<sub>40</sub> compared to Pf<sub>80</sub>, showing a J-curve shape? One possible explanation is the more pronounced and greater leg joint flexion and extension movements at the lower poling frequency, which are reported to provide a better

lactate clearance, partly explained by the leg muscles being substantial net lactate consumers during this specific exercise (Di Martino et al. 2000; Holmberg et al. 2006). It is most likely that the lower poling frequency, with more distinct muscle activation and with longer recovery phases also provides a more beneficial hemodynamic situation. At higher poling frequencies, although with lower peak pole forces per contraction, the relative time for reperfusion during the recovery phase is shorter which may compromise muscle perfusion (Saltin et al. 1998).

### Gross efficiency

In the current study, gross efficiency was 7–13% higher at Pf<sub>40</sub> versus Pf<sub>60</sub> versus Pf<sub>80</sub> at the two lower speeds. However, at the highest speed, Pf<sub>40</sub> and Pf<sub>60</sub> revealed almost equal gross efficiencies which were 11–13% higher than Pf<sub>80</sub>. We suggest that one primary reason for a lower gross efficiency at Pf<sub>80</sub> for all speeds is a difference in internal work, with greater ranges of motion in the hip and knee joints at this poling frequency (Tables 2, 3). Such an effect on efficiency has previously been shown in cycling, where the most efficient cadence increases with increasing workload (Foss and Hallen 2005). This has been explained by the need to recruit additional fast-twitch motor units as the workload increases, in order to sustain the higher power output at the higher work rates (Chavarren and Calbet 1999). The increase in the most efficient cadence with workload could be partly confirmed in the current study, as gross efficiency at Pf<sub>60</sub> increased relative to Pf<sub>40</sub> both showing similar values at the highest work rate (24 km·h<sup>-1</sup>). It can be assumed that at speeds >30 km·h<sup>-1</sup>, Pf<sub>60</sub> or even higher poling frequencies would become more efficient compared to Pf<sub>40</sub>, supported by findings in sprint skiing, demonstrating poling frequencies of ~70 cycles·min<sup>-1</sup> together with cycle lengths of ~7.5 m at maximal speeds up to 32 km·h<sup>-1</sup> (Stöggl and Müller 2009). A poling frequency of 40 cycles·min<sup>-1</sup> would require cycle lengths above 10 m at speeds greater than 24 km·h<sup>-1</sup>, a value that can be considered as getting out of reach even for elite skiers competing at international level.

### Breathing mechanics

An interesting aspect in double poling is that the same muscles that are active for propulsion also play a role in breathing (Holmberg and Calbet 2007). The ventilatory equivalents for oxygen (V<sub>E</sub>/VO<sub>2</sub>) and carbon dioxide (VE/CO<sub>2</sub>), indicators for ventilatory ‘efficiency’, were lower at Pf<sub>40</sub> compared to the other two poling frequencies at 24 km h<sup>-1</sup> (Fig. 5e), where the skiers were most physiologically loaded (~90% of maximum heart rate). Factors reported to be related to the mechanics of pulmonary

ventilation that may have influenced this are (1) a more favourable body position for gas exchange (Mure and Lindahl 2001) and (2) better muscular assistance during the expiration phase (Dempsey et al. 1990). The skiers had a greater hip flexion at Pf<sub>40</sub> and reached a probably more horizontal position of the thorax, a position that has been reported to be favourable for gas exchange and assists perfusion of the lung (Mure et al. 2000; Mure and Lindahl 2001). When using a 1:1 locomotor-breathing pattern at Pf<sub>40</sub> at all speeds, the skiers temporarily synchronize the end of the expiration and the start of the inspiration in that low position at the end of poling phase. Furthermore, the expiration has been described as being aided by a more intensive use of the abdominal muscles, which are one of the prime movers in double poling (Holmberg et al. 2005). A forceful contraction of the abdominal muscles has been proposed to facilitate and aid pulmonary ventilation during double poling (Holmberg et al. 2005), via a reduction in the end expiratory lung volume (Henke et al. 1988; Holmberg and Calbet 2007). Another interesting aspect related to breathing mechanics was the presence of two different breathing strategies at Pf<sub>80</sub> at the highest speed. Most skiers coupled their breathing to poling frequency using ~80 breathing cycles·min<sup>-1</sup> (1:1), but some were breathing every second pole thrust (1:2) using ~40 breathing cycles·min<sup>-1</sup>. The latter athletes may have limited their breathing frequency, i.e. using a higher tidal volume, in order to lower oxygen cost used for breathing also at the highest workload, as discussed above. In contrast, the 1:1 skiers most likely preferred to enhance their ventilation by increasing their breathing frequency up to ~80 breathing cycles·min<sup>-1</sup> in order to meet the higher ventilatory demands at the highest workload. A recent cross-country skiing study also demonstrated slight positive effects of coupling expiration and poling phase on pole force production, an aspect that has to be further investigated (Fabre et al. 2007).

In summary, we found that elite cross-country skiers generate higher forces during longer poling times and lower rates of force development and use greater ranges of joint motion at lower compared to higher poling frequencies. Moreover, the oxygen cost was highest at the highest poling frequency at all speeds, whereas lactate response showed a diverse pattern, indicating a J-curve, with the second lowest value at Pf<sub>40</sub>, the lowest at Pf<sub>60</sub> and the highest at Pf<sub>80</sub> when double poling at the highest speed.

These results may serve as a basis for better understanding of the double poling technique. As different poling frequencies imply diverse physiological as well as biomechanical demands, we suggest that elite cross-country skiers would benefit from including different frequencies in their training in order to vary their training load. Training at a low poling frequency could be used as a type

of supplemental specific strength training on skis which may be beneficial for two reasons: (1) Skiers train under similar biomechanical conditions as those observed at competition speeds with high forces and great joint angle ranges of motion; and (2) This type of training can be implemented, even at low and medium submaximal speeds, with a 30–40% lower oxygen cost and a blood lactate concentration lower than  $2 \text{ mmol}\cdot\text{L}^{-1}$ .

In contrast, double poling at higher frequencies up to 80 cycles per minute could be used to place higher cardio-respiratory loads and for coordinative purposes. Complementary low-frequency/low-to-medium intensity training could be very useful in kinds of locomotion such as double poling, demonstrating an open-kinematic chain according to the principle of specificity, and avoiding monotony in endurance sports such as cross-country skiing that are characterized by a large emphasis on large volumes of low-intensity training. We recommend that future studies elucidate the optimization of double poling frequency associated with performance, even at the higher speeds reached in the sprint event.

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