The effects of poling on energy consumption, kinematics and kinetics in roller ski skating

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Master thesis

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Abstract

The current study investigated the effect of poling on physiological, kinematic and kinetic responses at different velocities by comparing the G4 skating technique with (G4-P) and without (G4-NP) poling. The G4 involves a "strong side" with poling action and a "weak side" with arm swing. 17 elite male cross-country skiers performed 4-min submaximal tests at 10, 15 and 20 km·h^{-1} on a 2% inclined treadmill using G4-P and G4-NP. Physiological, kinematic and kinetic variables were assed with open- circuit indirect calorimetry, blood lactate analysis, Qualisys Pro Reflex system and roller skis integrated with two full bridged strain gauges. Gross efficiency (GE) was calculated by the external work rate against friction and gravity divided by the metabolic rate in aerobic steady state conditions. O_2 consumption, ventilation and blood lactate concentration were lower with G4-P than G4-NP at all velocities and thus, GE was higher in the two examined velocities with G4-P compared to G4-NP (11,1% vs 9,9%; 12,5% vs 10,6%; all $P < 0.05$). Longer cycle lengths at lower cycle rates, as well as less ski angling and edging were demonstrated with G4-P compared to G4-NP from low to high velocities, with a 15% difference in cycle length at high velocity (all $P < 0.05$). Force impulse was lower with G4-P compared to G4-NP for the "strong side" at low and high velocity (both $P < 0.05$). Rate of force development and peak force were lower for both strong and weak sides with G4-P compared to G4-NP, and the ski velocity was on average higher on the strong side for G4-P at all velocities (all $P < 0.05$). Altogether, these results demonstrated lower physiological demands and higher gross efficiency at a given work rate when elite skiers added poling to the G4 skating technique. At the same time, skiers increased their cycle lengths and showed significant changes in the cycle characteristics by increasing the ski velocity and reducing the applied ski forces of both the strong and weak sides when poling.

Key Words: cross-country skiing; blood lactate concentration; cycle length; biomechanical parameters; ski forces.

Introduction

Competitive cross-country skiing is regarded as a physical and technical demanding endurance sport (Holmberg et al. 2005). Initially, cross-country skiing included only classical time-trial races (Sandbakk et al. 2011a). From the mid-1980s, the skating technique was introduced, followed by a modification of the competitive program (Nilsson et al. 2004; Sandbakk et al. 2011b). In 2013, the elite cross-country skiers are challenged by distances from 1 to 50 km, performed as individual time-trials, mass start races or knockout heats (Sandbakk et al. 2012). In order to succeed in competitive cross-country skiing, several studies have shown that a high energy delivery capacity and an efficient technique is crucial (Andersson et al. 2010; Holmberg et al. 2006; Millet et al. 2003; Sandbakk et al. 2012).

Within the cross-country skating technique, different sub-techniques have been developed that can be considered as a gear system (gear 1-7) suitable for adjusting to different terrain and velocities (Anderson et al. 2010). The G4 technique is primarily used at flat terrain during high velocities, and is characterized by a poling action at every second leg push-off (Andersson et al. 2010). The G4 skating technique is also known as V2-alternate and 2-skate (Bilodeau et al. 1992: Boulay et al. 1994: Nilsson et al. 2004).

The variety in competition forms challenges the skiers to employ their upper and lower body to various extents (Hall et al. 2003). Even though the lower body is considered the main energy consumer in cross-country skiing, the upper body appears to be highly important for propulsion both in the classical and skating techniques (Pellegrini et al. 2011; Sandbakk et al. 2013; Smith et al. 1992). Sharing the workload over upper and lower limbs may affect metabolic rate at a given work rate, for example, when adding upper body work to cycling during a given work rate, the metabolic rate increased (Hoffman et al. 1996). However, the metabolic demand decreased at sub maximal work rates in movement patterns similar to cross country skiing when upper body work was added to lower limbs test (Millerhagen et al. 1983).

When sharing the workload in ski skating, elite skiers showed lower metabolic rate at a given work rate when poling was added to leg work in the G3 skating technique (Sandbakk et al. 2013). In G4 the arm swing movement is greater compared to G3 (Andersson et al. 2010). Although the skiers pole only on every other push-off in G4, it is suggested that skiers apply the poling forces more effectively during G4 compared to the G3 technique (Millet et al. 1998). When investigating the G3 skating technique, the higher gross efficiency (GE) with poling may be explained by the additional increase in cycle length, which is suggested to be a predominant factor on GE (Leirdal et al. 2011; Sandbakk et al. 2010; 2011b). The effect poling has on physiological responses and cycle characteristics has not yet been investigated in the G4 skating technique.

In addition, the effect of poling is also associated with changes in the legwork such as less inclined ski angulation and less angular movement in the ankle and knee joints (Sandbakk et al. 2013). The leg push-off in ski skating is performed in a zig-zag motion and the time to apply force is not limited by the velocity (Sandbakk et al. 2013). To date, ski forces have not been examined in the skating technique. However, analyses of pressure distribution in the soles indicate that when skiers approach maximal skiing velocity both rate of force development (RFD) and peak force (PF) are increased (Stöggl et al. 2011). How ski kinetics coincides with the poling action and changes in velocity requires further examination.

The purpose of this study was to investigate the effect of poling on physiological, kinematic and kinetic responses at different velocities by comparing the G4 skating technique with (G4-P) and without (G4-NP) poling. The hypothesis was that poling when G4-P would increase gross efficiency, cycle length and reduce ski forces compared to G4-NP.

Methods

Subjects

17 male elite cross-country skiers participated in this study. The skiers were all among the 20 best in the Norwegian Cup Series. Their anthropometric, physiological characteristics and FIS points are documented in Table 1. The experimental procedures employed were pre-approved by the Norwegian Regional Ethics Committee. To each skier the protocol and procedures were explained verbally prior to obtaining his written informed consent.

Table 1. Anthropometric, physiological characteristics and FIS points for the 17 elite male cross-country skiers.

N= 17	Mean ± SD
Age (years)	23.8 ± 3.8
Body height (cm)	180.0 ± 5.4
Body mass (kg)	73.7 ± 6.8
Body mass index (kg m^{-2})	22.7 ± 1.4
VO_{2peak} (L min^{-1})	5.2 ± 0.6 (1)
VO_{2peak} (ml $min^{-1}kg^{-1}$)	70.9 ± 4.3 (1)
International Ski Federation (FIS)	65 ± 23

(1) VO_{2peak} oxygen uptake measurements was assed during roller ski skating in the G3 skating technique.

Overall experimental design

The skiers performed submaximal tests using roller skis at 10, 15 and 20 $km \cdot h^{-1}$ at a 2% inclined treadmill employing the G4-P and the G4-NP technique. The arm swing movement in G4-NP simulated the pronounced upper body movement when G4-P. The submaximal tests were carried out with the two techniques in a random order. Gross efficiency was calculated by dividing work rate by metabolic rate expressed by a percentage (Sidossis et al. 1992). The work rate was calculated as the sum of power against gravity and frictional rolling forces (Sandbakk et al. 2010). The metabolic rate was calculated using gas exchange. To measure the ski kinetics, the roller skis were constructed with strain gauges, which has been validated by Hoset et al. (2013).

Instruments and materials

The skiers performed the roller ski skating using G4-P and G4-NP on a 6 × 3-m motor-driven treadmill (Bonte Technology, Zwolle, The Netherlands). The calibration of incline and velocity was assessed with the Qualisys Pro Reflex system and Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). The treadmill belt consisted of a surface covered with non-slip rubber, which allowed all of the skiers to use their own poles with special carbide tips (with a length = 90 ± 1% of body height). During testing the skiers were secured with a safety harness (Sandbakk et al. 2013). The same pair of Start roller skating skis with standard wheels was used by all of the skiers to minimize variations in rolling resistance (Start Skating 80, Startex, Hollola, Finland).

Before the roller ski tests, the rolling friction force (F_f) was determined by a towing test of the roller skis described by Sandbakk and colleagues (2010); *"the friction coefficient (μ) calculated by dividing F_f by the normal force (N), i.e., $\mu = F_f \times N^{1}$"*. In the current study an overall mean value of 0.021 was used to calculate work rate, based on less than 5% variation between the friction coefficient determined at different inclines and velocities.

The force measurement system was assessed with the two roller skis, which were instrumented with two full bridge strain gauges (VY 41-3/350, HBM Gmbh, Darmstadt, Germany) as shown in Figure 1. Each of the skis consisted of a wireless analogue sensor node with a radio transmitter and an integrated internal battery (V-Link MXRS, Microstrain Inc, Williston, VT, USA), which provided excitation for the full bridge strain gauges. Thus, data log were be transmitted wirelessly to a base station. Furthermore, data was acquired by the accompanying software NodeCommander 2.3.0. Two Kistler force platforms were assessed to validate the magnitude and direction of the forces, with one wheel on each platform (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland)). The error shown in the measurements was linear with the magnitude of the applied forces. Thus, by multiplying with a calibration coefficient for each strain gauge the error was removed. There were no differences between the left and right ski during 400 tests and six months of use, which indicated a high reproducibility. The data were evaluated using a MATLAB 7.12.0(R2011a) program. For more detailed description of the equipment, see Hoset et al. (2013).

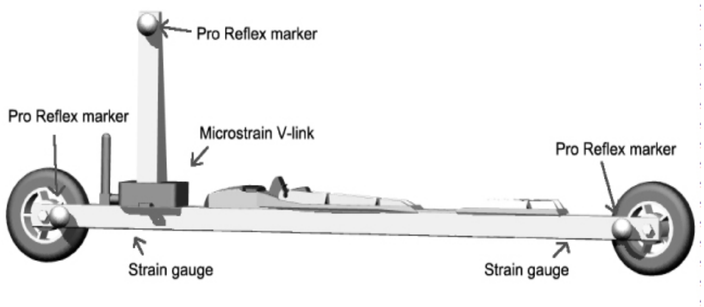


Figure 1. Illustration of the roller ski.

Prior to ventilatory measurements, the VO_2 and VCO_2 analyzers were calibrated using a known mixture of gases (16.00 ± 0.04% O_2 and 5.00 ± 0.1% CO_2, Riessner-Gase GmbH & Co, Lichtenfels, Germany) and a 3-L syringe for the expiratory flow meter calibration (Hans Rudolph Inc., Kansas City, MO) (Sandbakk et al. 2013). Ventilatory parameters were assessed employing open-circuit indirect calorimetry with an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany), which was validated by Foss and Hallen (2005). Heart rate was recorded simultaneously (Polar RS800, Polar Electro OY, Kempele, Finland). Furthermore, the lactate concentration in whole blood (5-µL collected from the fingertip) was analysed using the Lactate Pro LT-1710*t* kit (ArkRay Inc, Kyoto, Japan), as validated by Medbø and co-workers (2000). To evaluate the Rating of Perceived Exertion (RPE) for the lower, upper and whole body, the Borg scale (6-20) was assessed (Borg, 1970).

To monitor the poling action, 2 synchronized video cameras were placed in front and at the side of the treadmill (Sony Handcam DCR-VX2000E, Sony Inc., Tokyo, Japan). Thus, the entire movement range of the skier, skis and poles were visible (Sandbakk et al. 2011b). 15-second recordings were analyzed using the Dartfish Pro 4.5 program (Dartfish Ltd, Fribourg, Switzerland).

The Kistler force plate and a calibrated stadiometer were used to measure body mass and body height (Holtain Ltd., Crosswell, UK).

Test protocols

Training on the day before testing was standardized and consisted of low intensity training of 45 minutes and familiarization with the roller ski treadmill. In addition, the skiers performed a test-specific 20 minutes warm-up prior to each session of testing to ensure the skiers confidence with roller ski skating on a treadmill and to minimize the effect of learning. The submaximal tests and peak oxygen uptake test were conducted approximately 48 hours apart. The skiers drank a standard fluid with sugar and electrolytes during breaks.

Submaximal tests

The skiers performed 4 minutes submaximal tests at 10-, 15- and 20 km·h^{-1} at a 2% incline using the G4-P and G4-NP. Rests between the sessions were 1-, 2- and 3 minute respectively. All skiers reached aerobic steady state in oxygen consumption at 10- and 15 km·h^{-1}, which were used in the calculation of GE. The two different techniques were assessed in a randomized order. Ventilatory parameters, heart rate and roller ski kinematics and kinetics were recorded simultaneously during the last minute of each test. The concentration of lactate in the blood was measured immediately after each test and the skiers rated the RPE for the lower, upper and whole body.

Peak oxygen uptake

The peak oxygen uptake test was assed using the G3 skating technique at a 5% incline with an initial velocity of 16 km·h^{-1}. The velocity increased with 2 km·h^{-1} after the first and second minute, thereafter an increase of 1 km·h^{-1} every minute until exhaustion was reached (Sandbakk et al. 2013). The intention of the test was to measure the maximal effort while roller ski skating, whereas two out of three criteria needed to be fulfilled; *"1) a plateau in* VO_2 *despite increasing exercise, 2) a respiratory exchange ratio above 1.10, 3) a blood lactate concentration above 8 mmol·*L_{-1}*"* (Bassett and Howley, 2000). The oxygen consumption was measured continuously, and the average of the three highest consecutive 10 seconds was determined as VO_{2peak} (Bassett and Howley, 2000).

Calculation of gross efficiency

Gross efficiency was obtained while roller skiing on the treadmill in a steady state condition at 10- and 15 km·h^{-1} using G4-P and G4-NP. Gross efficiency was calculated by the external work rate performed by the entire body divided by the aerobic metabolic rate, and processed by using the product of VO_2 and oxygen energetic equivalent associated with standard conversion tables of Respiratory Exchange Ratio (RER) (Sandbakk et al. 2010; Peronnet et al. 1991). Work rate was calculated according to Sandbakk et al (2010) and considered to be only dependent on power against gravity (P_g) and roller friction (P_f):

$$P_g = m \cdot g \cdot sin\ (\alpha) \cdot v$$

$$P_f = (1 - PF) \cdot m \cdot g \cdot cos\ (\alpha) \cdot \mu \cdot v_{ski}$$

where m is the mass of the skier, g the gravitational constant (acceleration), α the angle of treadmill incline, v the belt velocity and μ the frictional coefficient. The velocity of the ski (v_{ski}) was calculated on individual basis as $v_{ski} = v/cos(orientation\ angle)$. In addition, calculation of P_f, body mass loading the skis was adjusted to earlier findings (Millet et al. 1998), which suggested that average vertical component of poling force on a 2% incline is approximately 5% of the body mass.

G4-P and G4-NP skating technique

The skiers performed the G4-P and G4-NP during the submaximal tests (Figure 2). The G4 skating technique consists of a strong side, where the legwork is supported by the poling action and a weak side, where the legwork is supported by the recovery arm swing of the poling movement. The skiers were instructed to employ similar arm swing movement in G4-NP as when G4-P based on comparison purposes.

G4-P

G4-NP

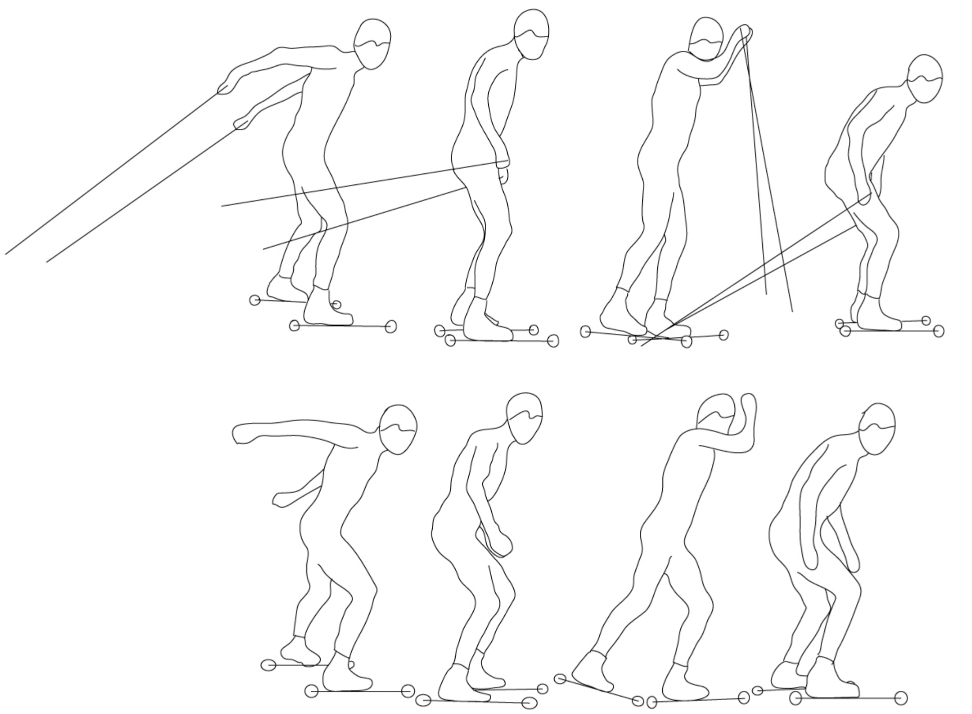


Figure 2. Illustration of G4 skating technique with (G4-P) and without (G4-NP) poling.

Biomechanical parameters

Kinetic- and kinematical variables were all recorded simultaneously during the last minute of the submaximal stages. One cycle movement included one right and one left skating stroke. Thus, the cycle began at ski lift-off the left ski and ended two ski lifts later (Sandbakk et al. 2013). The variables were averaged over 10 complete cycles. *Cycle time* (CT) was determined by the time of one cycle movement, and *cycle rate* (CR) was defined as the quantity of cycles per second. *Cycle length* (CL) is the covered distance on the treadmill during one cycle, and was calculated by velocity divided by CT (Sandbakk et al. 2010). *Poling time* (PT) was defined as the time from pole plant to pole lift-off, and *pole swing time* was calculated by subtraction of PT from CT.

Ski angles of the roller skis were defined as the angle relative to the forward direction of the treadmill belt, which was determined as 0°. Ski angles were calculated during the ground contact phase from three markers on each roller ski. Ski edging of the roller skies was defined as 0° when the wheels were perpendicular to the treadmill belt, and was calculated as the rotation in angles around an axis parallel to the roller skis (Hoset et al. 2013). Center of Pressure (CoP) was measured from posterior heel point to ski binding using a standard EU shoe size 43, as shown in Figure 3. CoP was defined as the relative value from 0 (posterior heel point) to 1 (ski binding).

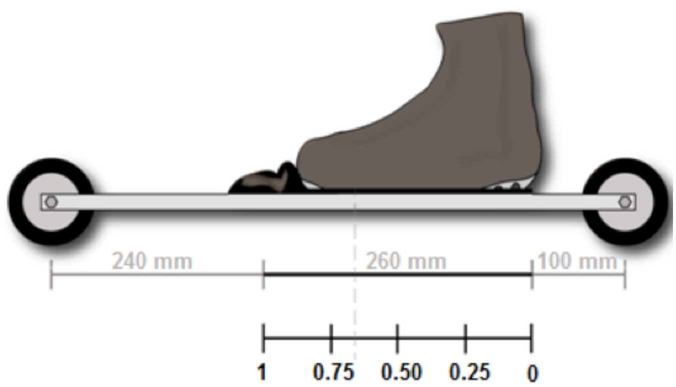


Figure 3. Illustration of the CoP measurements, from 0 value at posterior heel point to 1 at ski binding.

The kinetic variables are shown in the force graph in Figure 4. *Ground contact phase* was defined as the time of each ski was in ground from ski plant to ski lift-off. *Swing time phase* was defined as cycle time minus ground contact time for each ski. *Peak force* (PF) was defined as the highest value measured during ground contact phase, whereas force minimum was defined as the lowest value during ground contact with a subsequent increase of force to the peak force. *Impact force* is the highest force produced immediately after ski plant. *Force impulse*, i.e., the integral of force over time was calculated over the time from force minimum to ski lift-off. Rate of force development (RFD) was calculated by dividing force by time, from force minimum to peak force. In addition, the terms *gliding time* and *push-off time* represented in general the skiers' movement through force appliance, and were respectively defined as the time from ski plant to force minimum, and the time from force minimum to ski lift-off.

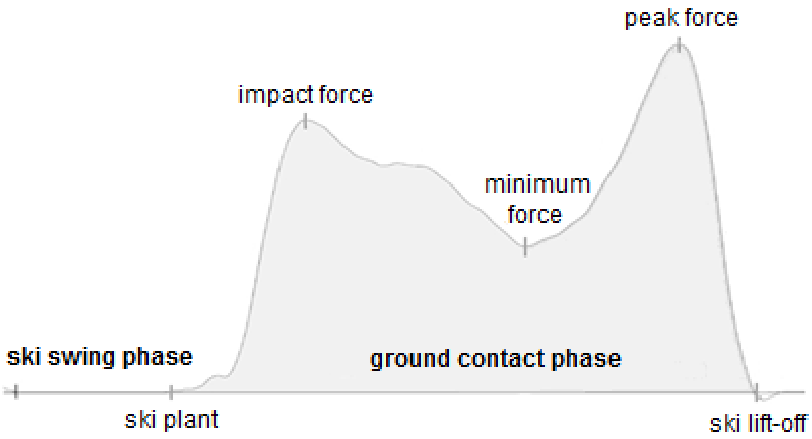


Figure 4. The force plot for one ski during a cycle movement from ski plant to ski lift-off.

Statistical analysis

All data were checked for normality, and then presented as mean and standard deviation (SD). To evaluate differences between techniques and possible interactions between velocity and technique, the ANOVA analysis using two-way repeated measures was assessed. To locate pairwise differences, the paired samples *t*-test was assessed. Intraclass correlation coefficients > 0.95 was demonstrated on the treadmill during repeated measurement of the kinematic and physiological parameters. Statistical significance was set at $P < 0.05$. All of the statistical tests were processed using SPSS 11.0 Software for Mac (SPSS Inc., Chicago, IL).

Results

Physiological responses and gross efficiency

The O_2 consumption, ventilation and breathing frequency were lower with G4-P than G4-NP at all velocities (Table 2, all $P < 0.05$). ANOVA analysis showed a significant effect of increasing velocity on O_2 with increasing differences, leading to as much as 16% lower values with G4-P at 20 km·h^{-1} ($P < 0.05$). Tidal volume, RER and the ventilatory equivalent did not differ between G4-P and G4-NP at the low (10 km·h^{-1}) velocity; however at moderate (15 km·h^{-1}) and high (20 km·h^{-1}) velocity there were lower values with G4-P (Table 2, all $P < 0.05$). The aerobic metabolic rate was constantly lower at comparable work rates with G4-P, and thus, gross efficiency was higher in G4-P compared to G4-NP at 10 and 15 km·h^{-1} (Figure 5, both $P < 0.05$). Although it was not possible to obtain a valid measure at intensities above an aerobic steady state, physiological responses indicated that GE was also higher with G4-P at the high velocity.

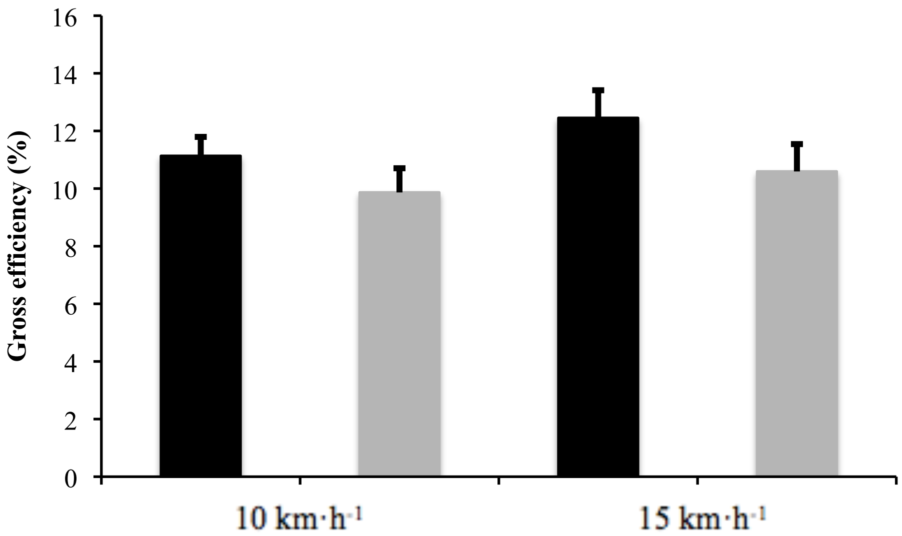


Figure 5. Gross efficiency at 10 km h^{-1} and 15 km h^{-1} for the 17 cross-country skiers using the G4 skating technique with poling (G4-P in black) and without (G4-NP in grey) poling when roller skiing on a treadmill at 2% incline.

The lower and whole body Borg RPE were higher with the G4-NP compared to G4-P at all velocities (Table 2, all $P < 0.05$). Blood lactate did not differ at low velocity, but at moderate and high velocity blood lactate values were lower with G4-P (both $P < 0.05$).

Table 2 Physiological responses, work rate and gross efficiency for the 17 elite male skiers during low (10 km h^{-1}), moderate (15 km h^{-1}) and high velocity (20 km h^{-1}) of roller skiing utilizing the G4 skating technique with (G4-P) and without (G4-NP) poling (means ± SD).

Variable	Technique	10 km h^{-1}	15 km h^{-1}	20 km h^{-1}
VO_2 (L min^{-1})	G4-P	2.20 ± 0.21*	2.97 ± 0.30*	3.82 ± 0.37*
	G4-NP	2.50 ± 0.27	3.45 ± 0.34	4.55 ± 0.41
VO_2 (ml min^{-1} kg^{-1})	G4-P	29.6 ± 1.8*	40.0 ± 2.9*	51.5 ± 3.8*
	G4-NP	33.7 ± 2.7	46.5 ± 3.6	61.4 ± 4.4
Ventilation (L min^{-1})	G4-P	54 ± 7*	71 ± 9*	98 ± 13*
	G4-NP	60 ± 8	86 ± 9	136 ± 16
Breathing frequency (min^{-1})	G4-P	29 ± 4*	33 ± 4*	37 ± 6*
	G4-NP	31 ± 5	36 ± 5	45 ± 8
Tidal volume (L)	G4-P	1.86 ± 0.23	2.20 ± 0.29*	2.67 ± 0.38*
	G4-NP	1.98 ± 0.36	2.41 ± 0.36	3.09 ± 0.56
Oxygen uptake per breath (L)	G4-P	0.077 ± 0.013*	0.092 ± 0.013*	0.105 ± 0.016
	G4-NP	0.083 ± 0.017	0.098 ± 0.019	0.104 ± 0.018
Ventilatory equivalent (VE/VO_2)	G4-P	24.5 ± 2.5	23.9 ± 1.8*	25.7 ± 2.2*
	G4-NP	24.2 ± 1.4	24.8 ± 1.6	20.0 ± 3.0
Heart rate (beats min^{-1})	G4-P	114 ± 13*	135 ± 14*	160 ± 12*
	G4-NP	122 ± 12	149 ± 13	175 ± 11
Respiratory exchange ratio	G4-P	0.84 ± 0.04	0.84 ± 0.03*	0.86 ± 0.04*
	G4-NP	0.84 ± 0.04	0.87 ± 0.03	0.96 ± 0.06
Blood lactate (mmol L^{-1})	G4-P	1.1 ± 0.3	1.1 ± 0.3*	2.7 ± 1.6*
	G4-NP	1.1 ± 0.2	1.5 ± 0.6	4.9 ± 2.9
Borg RPE scale upper body	G4-P	7.4 ± 1.3	9.8 ± 2.3	12.7 ± 1.9
	G4-NP	6.9 ± 1.5	9.2 ± 2.8	12.0 ± 4.2
Borg RPE scale lower body	G4-P	7.8 ± 1.3*	10.6 ± 2.1*	13.3 ± 1.3*
	G4-NP	8.9 ± 1.5	13.0 ± 1.6	16.5 ± 1.6
Borg RPE scale whole body	G4-P	7.6 ± 1.5*	10.3 ± 2.0*	13.4 ± 1.4*
	G4-NP	8.4 ± 1.5	12.5 ± 1.7	15.8 ± 1.9
Work rate (W)	G4-P	83 ± 8	125 ± 12	166 ± 17
	G4-NP	83 ± 8	125 ± 12	166 ± 17
Aerobic metabolic rate (W)	G4-P	744 ± 69*	1005 ± 98*	1299 ± 124*
	G4-NP	849 ± 93	1175 ± 112	1581 ± 140
Gross efficiency (%)	G4-P	10.72 ± 0.65*	12.45 ± 0.96*	
	G4-NP	9.91 ± 0.78	10.59 ± 0.94	

* Statistically significantly different from the corresponding value for G4-NP at the same velocity ($P < 0.05$)

Kinematics

The cycle length and cycle rate increased with velocity in both techniques (Figure 5 and Figure 6; both $P < 0.05$). The skiers showed longer cycle length, lower cycle rate and longer cycle time with G4-P compared to G4-NP at all velocities, and the differences between techniques increased with velocity, being approximately 15% at 20 km h^{-1} (all $P < 0.05$).

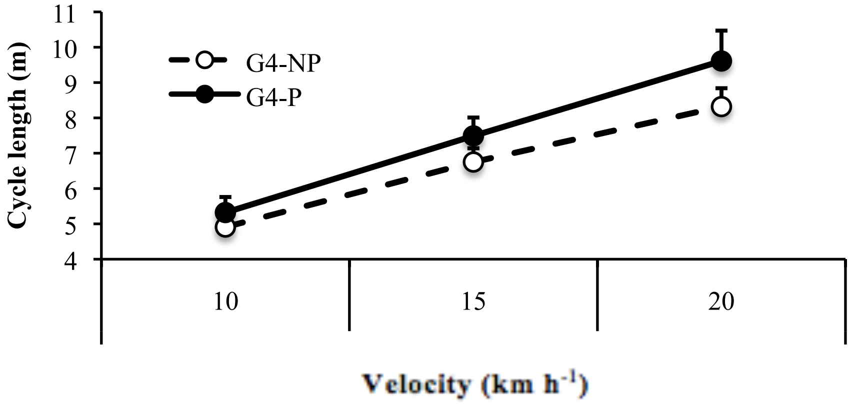


Figure 6. Cycle length at 10, 15 and 20 km h^{-1} for the 17 subjects with (G4-P) and without (G4-NP) poling.

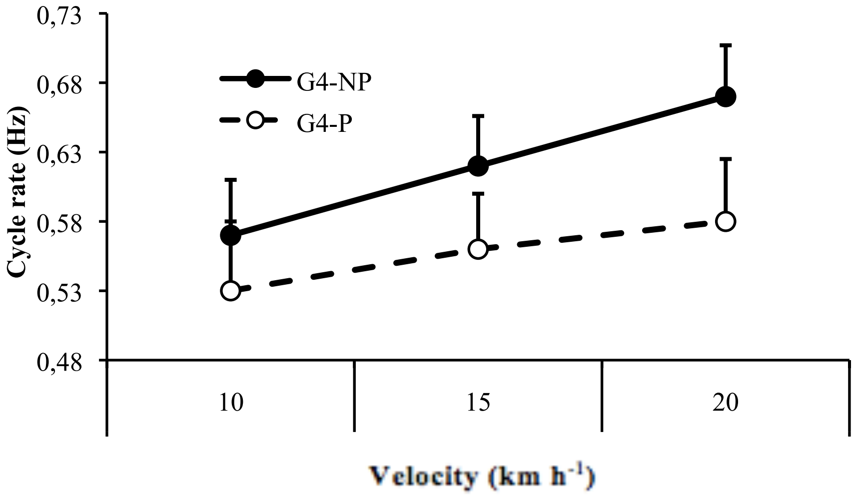


Figure 7. Cycle rate at 10, 15 and 20 km h^{-1} for the 17 subjects with (G4-P) and without (G4-NP) poling.

Poling time decreased with increasing velocity, and was significantly shorter when comparing low and high velocity, respectively (0.64 ± 0.06 vs 0.37 ± 0.02, $P < 0.05$). The poling time decreased with approximately 20% from both low to moderate velocity, and from moderate to high velocity (both $P < 0.05$). Relative to the total cycle time, the poling time reduced from being approximately 30% of the whole cycle at low velocity to being 20% at high velocity ($P < 0.05$). Poling swing time was shorter at low velocity compared to high velocity (1.22 ± 0.10 vs 1.31 ± 0.11, $P < 0.05$).

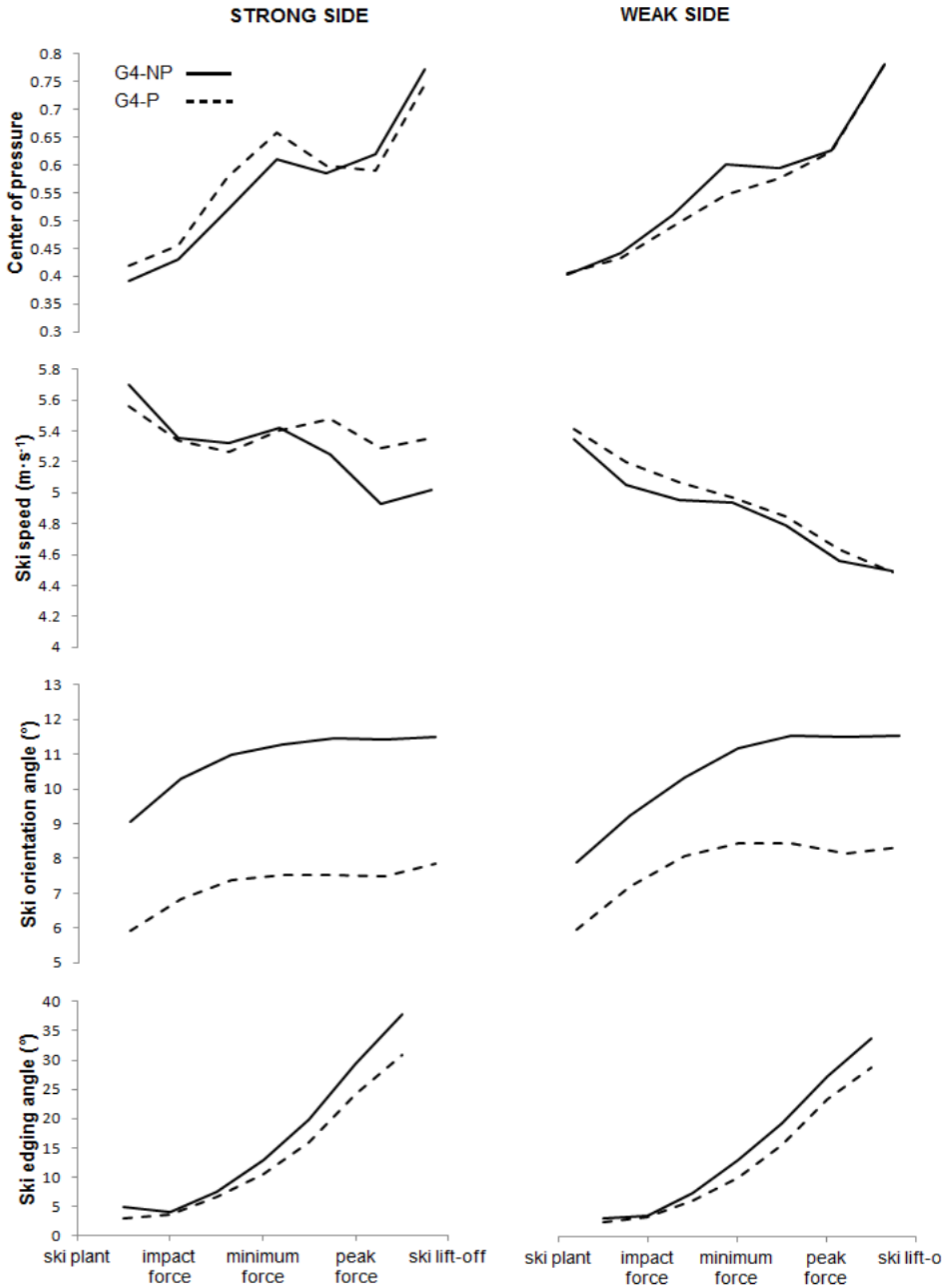
Ski swing time was higher for G4-P compared to G4-NP at all velocities for the weak side (Table 4, all $P < 0.05$), but did not differ at the strong side at low and moderate velocity. The gliding time did not differ when comparing G4-P and G4-NP on the weak side, but G4-P showed longer gliding time at all velocities for the strong side (Table 4, all $P < 0.05$). The ski push-off time was independent of technique, side and velocity.

Table 4. Cycle characteristics divided in strong – and weak side for the 17 elite male skiers during 5-min sessions of roller skiing with (G4-P) and without (G4-NP) poling at different velocities (means ± SD).

		Strong side			**Weak side**		
Variable		**10 km h^{-1}**	**15 km h^{-1}**	**20 km h^{-1}**	**10 km h^{-1}**	**15 km h^{-1}**	**20 km h^{-1}**
Ski swing time (s)	G4-P	0.66 ± 0.08	0.62 ± 0.06	0.60 ± 0.07	0.80 ± 0.10	0.76 ± 0.07	0.71 ± 0.06
	G4-NP	0.67 ± 0.07	0.60 ± 0.05	0.53 ± 0.04*	0.69 ± 0.06*	0.63 ± 0.06*	0.56 ± 0.06*
Ski gliding time (s)	G4-P	0.82 ± 0.18	0.71 ± 0.10	0.67 ± 0.09	0.72 ± 0.16	0.60 ± 0.11	0.57 ± 0.13
	G4-NP	0.66 ± 0.11*	0.58 ± 0.05*	0.54 ± 0.06*	0.66 ± 0.11	0.59 ± 0.09	0.54 ± 0.06
Ski push-off time (s)	G4-P	0.44 ± 0.15	0.49 ± 0.07	0.46 ± 0.06	0.40 ± 0.11	0.45 ± 0.11	0.45 ± 0.12
	G4-NP	0.45 ± 0.09	0.46 ± 0.05	0.42 ± 0.05	0.43 ± 0.09	0.42 ± 0.08	0.40 ± 0.06

*Statistically significantly different from the corresponding value for G4-P at the same velocity ($P < 0.05$).

For ski angling, edging, CoP and velocity of ski, the largest differences between techniques were shown at high velocity, as illustrated with the average values of all skiers from ski plant to ski lift-off (Figure 5). More specifically, ski angling and edging were higher for G4-NP than for G4-P at all velocities and in both strong and weak side (all $P < 0.05$). Velocity of ski and CoP did not differ for the weak side at all velocities when comparing G4-NP to G4-P. However, at high velocity on the weak side, the CoP at force minimum, and the velocity of ski at peak force and at ski lift-off showed significant differences when comparing G4-P and G4-NP (all $P < 0.05$). At the same time as the poling action was executed on the strong side in G4-P, higher velocities for the skis were demonstrated for the strong side with G4-P and compared to both sides with G4-NP, as well as more forward CoP (all $P < 0.05$). The higher velocity of skis for the weak side with G4-P compared to G4-NP coincides with the higher velocities in skis at ski lift-off with G4-P for the strong side.



Figur 5. CoP, velocity of ski, ski angles and edging in average values of all skiers for the strong and weak side from the ski plant to ski lift-off with 2 % incline at 20 km h^{-1}. Dotted lines show the G4 skating technique with poling (G4-P), and black lines show without (G4-NP) poling.

Kinetics

The force impulse in G4-P was lower than G4-NP at low and high velocities for the strong side (Table 5, both $P < 0.05$). The impact force did not differ between G4-P and G4-NP when comparing the strong and weak sides at any velocity. The peak force increased with velocity for both G4-P and G4-NP, and both the strong and the weak side showed lower peak force in the G4-P compared to G4-NP at all velocities (all $P < 0.05$). The force minimum showed lower values for the strong side with G4-P compared to G4-NP at high velocity ($P < 0.05$). The rate of force development increased with increasing velocity and was higher with G4-NP compared to G4-P for both sides at all velocities (all $P < 0.05$).

Table 5. Ski forces divided in strong – and weak side for the 17 elite male skiers during 5-min sessions of roller skiing with (G4-P) and without (G4-NP) poling at different velocities (means ± SD).

		Strong side			**Weak side**		
Variable		**10 km h^{-1}**	**15 km h^{-1}**	**20 km h^{-1}**	**10 km h^{-1}**	**15 km h^{-1}**	**20 km h^{-1}**
Impact force (N)	G4-P	773 ± 74	793 ± 77	818 ± 83	795 ± 74	796 ± 80	818 ± 90
	G4-NP	783 ± 75	798 ± 74	824 ± 74	780 ± 61	815 ± 65	843 ± 64
Force minimum (N)	G4-P	592 ± 75	497 ± 67	440 ± 80	689 ± 86	622 ± 78	555 ± 80
	G4-NP	595 ± 83	519 ± 60	387 ± 72*	631 ± 78	560 ± 71	449 ± 69
Peak force (N)	G4-P	760 ± 115	867 ± 142	996 ± 151	864 ± 118	956 ± 138	1067 ± 130
	G4-NP	1009 ± 127*	1171 ± 136*	1337 ± 138*	1003 ± 125*	1172 ± 142*	1325 ± 167*
Rate of Force Development (N s^{-1})	G4-P	799 ± 262	1241 ± 464	2029 ± 433	1022 ± 484	1583 ± 824	2332 ± 1280
	G4-NP	1588 ± 712*	2413 ± 733*	3774 ± 861*	1702 ± 711*	2851 ± 1180*	4069 ± 1372*
Force impulse (Ns)	G4-P	237 ± 121	292 ± 77	276 ± 63	252 ± 82	285 ± 83	303 ± 84
	G4-NP	317 ± 75*	314 ± 58	303 ± 55*	283 ± 67	293 ± 67	288 ± 47

*Statistically significantly different from the corresponding value for G4-P at the same velocity ($P < 0.05$).

Discussion

In the current study, the effect of poling on physiological, kinematic and kinetic responses at different velocities was examined by comparing the G4 skating technique with (G4-P) and without (G4-NP) poling. The main findings were as follows; G4-P demonstrated lower physiological demands than G4-NP at all velocities and thus, the hypothesis that gross efficiency is increased by the addition of poling was confirmed. Furthermore, longer cycle lengths and lower cycle rates were found with G4-P at all velocities, with higher ski velocities caused by the poling phase and less angling and edging of the skis in G4-P. For the strong side, the force impulse was lower at low and high velocity with G4-P, whereas peak force and RFD were reduced with G4-P both for the strong and the weak sides at all velocities.

Physiological responses and gross efficiency

The current findings demonstrated lower metabolic rate at a given work rate with the use of poling in the G4 skating technique, and a corresponding enhanced GE of the technique. The blood lactate increased at a given work rate with G4-NP, together with an increase in cardiorespiratory response. These findings coincided with the corresponding higher cycle rate found for G4-NP at a given work rate. The findings of lower metabolic demands when combining upper and lower body work at sub maximal velocities is in accordance with recent literature, which previously investigated the effect of poling in the G3 skating technique where the upper-body work is even more pronounced than with the G4 technique (Sandbakk et al. 2013). In cycling, when leg cycling without arm movements was compared to combined leg and arm cycling at similar work rates, the metabolic cost increased (Hoffman et al. 1996). The outcome of external work produced from the upper body in arm cycling compared to poling in ski skating may explain the difference in metabolic costs. Since it is demonstrated a superior force effectiveness of the propulsive poling forces, which has been shown to be high when poling in both G3 and G4 skating technique (Smith et al. 1992; Millet et al. 1998; Pellegrini et al. 2011). Together, the current findings indicate that the effect of poling contributed to additional propulsive forces, leading to several physiological benefits at a given work rate when G4-P compared to G4-NP.

Kinematics

In the present study, the skiers showed longer cycle length and lower cycle rate with G4-P compared to G4-NP at all velocities. When velocity increased the skiers showed increased differences in the cycle characteristics between G4-P and G4-NP. Lower CR and longer CL coincided with higher gross efficiency with G4-P when compared to G4-NP. This is supported by several studies that demonstrate that longer CL coincides with higher efficiency or better performance (Bilodeau et al, 1996: Rundell & McCarthy 1996: Stöggl & Müller 2009: Sandbakk et al 2010). Furthermore, higher cycle rate may increase the total metabolic cost of unloaded movement (i.e., the energy cost of moving arms and legs) (Leirdal et al. 2011). The longer CL and higher GE when G4-P found in this study indicate that the poling impulse is important for the effectiveness of the technique. The relationship between longer CL and added poling is in accordance with Sandbakk et al. (2013), which found longer CL and lower CR when the poling movement was added in the G3 skating technique. When excluding the poling action in both the G3 and G4, the skiers seem to compensate by increasing the frequency.

In the current study, ski angles and edging of the roller skis were in average higher with G4-NP than with G4-P in both strong and weak side at all velocities. Narrower ski angles with G4-P is probably due to the fact that poling forces are more forward directed than the ski forces, which leads to more forward directed overall propulsion for each cycle. This rationally leads to a greater forward angle and total component of the centre of mass at a given velocity, which may coincide with longer CL. These results are in line with previous findings of Sandbakk et al. (2012; 2013), which suggested that different velocities and terrain may affect ski angles and edging, and that the effect of poling results in less sideways (zig-zag) movement.

Velocities of the skis were maintained higher during a cycle with G4-P. The effect of poling on the acceleration of the ski was shown on the gliding ski immediately after the poling action started, and contributed to higher velocities of the skis. This was followed by increased ground contact time (i.e., longer gliding time during a cycle). Additionally, a more forward CoP for the strong side was demonstrated with G4-P. This result indicate more forward positioned skiers when poling on the strong side, by leaning forward before the poling action and thus, possibly creating favourable poling positions. These findings are in accordance with Stöggl et al. (2009), who investigated the CoP using pressure distribution insoles in the G2 skating technique on uphill terrain, and found a more forward CoP for the strong side. The difference between strong and weak side may be greater in the G4 skating technique. Since the G4 is used in easy terrain and may give the skiers longer cycle time and thus, longer time to reposition compared to G2 skating technique, which is used in uphill terrain.

Kinetics

The current study demonstrated lower force impulse on the strong side when comparing G4-P and G4-NP at low and high velocity. Here, the force impulse was used as an indicator of the applied ski forces in the push-off phase and contained both the eccentric and the concentric phases of the push-off. Pilot testing indicated that the concentric phase, which generates the propulsion, begins just prior to the peak force as in other countermovement exercises. Overall, the lower PF at all velocities for both sides with G4-P indicate that less propulsive force is produced from the lower limbs compared to G4-NP. Thus the addition of poling provides the opportunity to increase the total power output with less force distributed over the legs. This probably makes it less demanding for the legs, which were demonstrated by the lower RPE found for the legs when G4-P.

This investigation found lower PF and RFD in both strong and weak side with G4-P compared to G4-NP at all velocities. The constantly lower PF on the strong side in G4-P was expected, and supports that skiers apply some of the body weight into the poles, and thus, less leg forces are applied with G4-P. Both PF and RFD increased with increasing velocity for strong and weak side with G4-P and G4-NP. These findings are in line with previous suggested statements that skiers are dependent of higher PF and RFD when approaching maximal skiing velocity (Stöggl et al. 2011). It is suggested that higher skiing velocities coincide with higher cycle rate that result in shorter leg push off time, and therefore dependent of higher RFD (Stöggl et al. 2011). Altogether, reduced ski forces measured for G4-P indicate that the effect of poling for every second leg push-off allows the skiers to produce less ski forces in both the strong and weak side by sharing the workload over upper and lower limbs.

Practical implications

The current study investigated the effects of poling in the G4 skating technique, and demonstrated how skiers can distribute the work over the upper and lower limbs. Poling contributed to additional propulsive forces. The lower metabolic demands at a given work rate for G4-P resulted in reduced demands for the lower limbs and enhanced GE. The understanding of how the poling movement increases propulsion and off-loads the legs for every second leg push-off in G4 may be important knowledge for skiers and coaches understanding of optimizing their individual technical strategy.

Methodological considerations

The force impulse was used as an indicator of the applied ski forces in the push-off phase, and was calculated from force minimum to ski lift-off. However, this phase contains an eccentric contraction prior to the concentric push-off that primarily produces propulsion. These two phases cannot be divided without movement analysis of the lower limb. Thus, the calculation of propulsion from the concentric contraction in the push-off, is beyond the scope of this paper, but important for further examination on this topic.

Conclusion

In the current study, lower physiological demands at a given work rate were found by comparing G4-P and G4-NP at different velocities. This indicates that the skiers distribute work over the lower and upper body, which leads to a less demanding situation. The skiers increased their cycle lengths and showed significant changes in the cycle characteristics by increasing the ski velocity and reducing the applied ski forces of both the strong and weak sides with G4-P, as well as corresponding lower RPE compared to G4-NP. More research is needed to understand the influence of specific ski and poling forces variables on efficiency in the skating techniques at different velocities and inclines.

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