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The influence of technique, strength and power on submaximal force production and gross efficiency during isolated upper-body poling in cross-country skiers

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Abstract

Previous studies have shown that upper-body strength and power are associated with work economy or efficiency in various types of locomotion. However, isolated upper-body work has not yet been investigated, and the mechanisms related to these relationships have not been studied in detail. Therefore, the present study investigated gross efficiency (GE) during isolated upper-body poling, and the influence of technique, maximal strength and power on GE. Eleven male elite cross-country skiers performed three stages of 4-min submaximal poling at low, moderate and high intensity (submaximal 1, submaximal 2 and submaximal 3), and an 8-second maximal sprint using a modified poling ergometer. GE was calculated by external workrate divided by metabolic rate in submaximal stages. Poling forces were measured with a force cell, and poling displacement and velocity were measured using a motion capture system. During the submaximal tests, power per stroke (PPS) was calculated as total work produced per stroke, cycle rate (CR) as the reciprocal of the time used per cycle and poling length (PL) as the displacement of the arms during the poling movement. During the 8-sec maximal poling test, specific power was measured as the product of force and velocity averaged over the period of 8-s. Mean rate of force development (RFD_{mean}) and rate of force development peak (RFD_{peak}) was measured as delta force divided by delta time (dF/dT). Furthermore 1 repetition maximum (1RM) pull-down and pull-over was measured in a pull-down apparatus. There was a linear relationship between metabolic rate and workrate, and an positive effect of workrate on GE. Specific power showed low non-significant correlations with GE, but a significant correlation with workrate in submaximal 3 ($r = 0.63$, $p = 0.04$). Furthermore, PPS during submaximal poling correlated significantly with all workrates, and GE on the submaximal 3 (all $P < 0.05$). 1RM pull-down and pull-over did not correlate significantly with gross efficiency in submaximal poling, but correlated significantly with workrate in submaximal 3. In conclusion, it seems like upper-body poling shows linear metabolic workrate relationships, and that most of the differences in GE can be explained by workrate differences. Furthermore, a high power per stroke seems important to obtain high workrates and high gross efficiency, whereas maximal strength and sprint power are related to the conversion of forces into power per stroke.

Key words: One repetition maximum, Double poling, specific power, Gross efficiency, Oxygen consumption.

Introduction

Cross-country skiing is a whole-body endurance sport where the combination of upper-body poling and leg push-offs produce propulsion in many different skiing techniques, terrains and competition forms. Energy delivery capacity and mechanical efficiency are two key factors in cross-country skiing performance (Sandbakk et al. 2010; Sandbakk et al. 2012). Energy delivery capacity is considered to be essential in endurance sports, whereas cross-country skiers are shown to be among those with the highest oxygen uptake ($\dot{V}O_{2\max}$) (Holmberg et al. 2007; Ingjer 1991). Additionally, the ability to convert metabolic energy into external power and speed (i.e., mechanical efficiency) is of importance to cross-country skiing performance (Sandbakk et al. 2010; Sandbakk et al. 2012). Although not yet scientifically proven, technique, strength and power are suggested to influence mechanical efficiency in cross-country skiing (Sandbakk et al. 2010; Hoff et al. 1999). Especially the contribution of the upper-body seems important for skiing efficiency (Sandbakk et al. 2012).

Efficiency can be expressed differently within sport performance, and is usually separated into gross efficiency or work economy (Sandbakk et al. 2010; Hoff et al. 1999). Gross efficiency is calculated by workrate divided by metabolic rate, where efficiency is presented as a percentage of metabolic rate (Sandbakk et al. 2010). Work economy is calculated from the oxygen uptake at steady state and respiratory exchange ratio (RER) without knowing the workrate (Hoff et al. 1999). In this study, efficiency is expressed by gross efficiency based on the discussion presented by Ettema and Loras, (2009), where gross efficiency is considered to be the most applicable way to express efficiency for the entire body (locomotion system). By employing gross efficiency the ability to evaluate metabolic rate at different workrates gives a detailed insight into the energy conversion system of the human body.

Gross efficiency is demonstrated to differ between national and international level cross-country skiers (Sandbakk et al. 2010). It was shown that international level skiers tended to use longer cycle lengths and lower cycle rates at given workrates, and would therefore reach higher speeds. In addition to a higher energy delivery capacity, it was discussed whether this was caused by better technique or technique-specific power, since maximal strength of the upper and lower limbs did not differ between performance levels. Movement characteristics were further examined by Stöggl et al. (2007), who showed that faster skiers produced longer cycle length at equal cycle rates in various techniques. The underlying explanation for these

differences might be explained by different factors; greater strength abilities may enhance the ability to produce force and thereby longer cycle lengths (Lindinger & Holmberg 2010), and the technical factors may increase the propulsive force component produced in the push (Sandbakk et al. 2010).

Maximal strength and power have been shown to be important factors related to cross-country skiing performance (Stöggl et al. 2009; Hoff et al. 1999). The extent to which 1 repetition maximum (1RM) is associated with skiing performance seems technique dependent, i.e., the relationship between maximal strength exercise and the skiing technique performed (Stöggl et al. 2009). It seems that the influence of strength reaches a plateau were other physiological factors are of greater importance (Sandbakk et al. 2010; Losnegard et al. 2011). However, the general view is that there are still possibilities to improve skiing performance through enhanced strength in elite cross-country skiing, and especially for the upper-body (Stöggl et al. 2009; Hoff et al. 1999; Losnegard et al. 2011).

Upper-body work through poling is of great importance to attain forward propulsion in various cross-country skiing techniques (Holmberg et al. 2005; Stöggl & Muller. 2009). The traditional way to investigate poling in cross-country skiing is through examinations of the double poling (DP) technique (Holmberg et al. 2005; Sandbakk et al. 2012; Stöggl & Muller 2009). However, DP includes both upper- and lower body-work, with different roles for the arms, trunk and legs (Holmberg et al. 2005). Holmberg and colleagues (2006) showed that the contribution of legs during double poling enhanced both the energy delivery capacity and work economy. However, no study to date has, to the best of our knowledge, studied gross efficiency in relation to maximal strength and power parameters during isolated upper body work in more detail with elite cross-country skiers.

Knowing all this, the purpose of the present study was to investigate how maximal strength and power influence force production and gross efficiency during isolated upper-body poling exercise. It was hypothesized that higher maximal strength and power leads to greater power per stroke during submaximal exercise, and thereby a higher gross efficiency.

Methods

Subjects

11 male elite cross-country skiers volunteered to participate in the study. Their demographic, anthropometric, and performance characteristics (in accordance to the FIS system (2012)) are presented in Table 1. The experimental procedures employed were pre-approved by the Norwegian Regional Ethics Committee and the protocol and procedures explained verbally to each subject prior to obtaining his written informed consent prior to participate. In order to participate, the subjects had to be performing upper body strength training twice a week over the last 3 months and include upper body training in their daily endurance training.

Table 1. Anthropometric characteristics, performance level (FIS-points) and maximal aerobic capacity for the elite cross-country skiers involved in this study.

	Parameters Mean \pm SD
Age (years)	25 \pm 6
Body height (cm)	180 \pm 3
Body weight (kg)	75 \pm 7
FIS-points	76 \pm 21
VO ₂ peak simulated poling (mL min ⁻¹ kg ⁻¹)	47.9 \pm 8.3
VO ₂ max running (mL min ⁻¹ kg ⁻¹)	73.0 \pm 3.6

The overall experimental design

To determine the influence of maximal strength and power on submaximal force production and gross efficiency during upper body poling, various 1RM, specific power and ergometer measurements were assessed in a cross-sectional design. 1RM was assessed in a specific pull-down and pull-over exercise. Specific power was assessed during 8-s maximal simulated double poling. Metabolic responses and workrate was measured during three stages of 4-min submaximal poling in a modified poling apparatus.

Instruments and materials

Ventilatory parameters were assessed employing Metamax 3 portable analyser (Cortex Biophysik GmbH, Leipzig, Germany), the VO₂ and VCO₂ analyzers were calibrated using a known mixture of gases O₂ (16.00%) and CO₂ (4.00%) prior to each test day, and the expiratory flow meter calibrated with a 3-L syringe prior to each test (SensorMedics, Yorba Linda, CA). Movement characteristics were recorded using the Qualisys Ocus system

(Qualisys AB, Gothenburg, Sweden), six cameras captured four markers placed on the poling ergometer (one on each pulling rope and handle bar). The difference between the initial position and the end position of these markers during the pull phase, both left and right, was used to calculate displacement using a 5-point differentiating filter. Heart rate was recorded with a heart rate monitor (Polar RS800, Polar Electro OY, Kempele, Finland). In addition, lactate concentration was measured using Biosen C-Line Sport (EKF Industrial Electronics, Magdeburg, Germany). Both the submaximal poling and 8-s specific sprint power were performed in a modified Concept 2SkiErg (Morrisville, Vermont, US). Force and velocity characteristics were measured by a force cell mounted on the ergometer (Noraxon U.S.A. inc, Scottsdale, Arizona, US). A sledge hockey seat was mounted to a platform where the subjects sat with their feet strapped during the entire test to ensure that no work could be done by the lower extremities (Fig.1). 1RM was measured using a pull-down apparatus (Technogym corp, New Jersey, US) with a custom made handlebar attached to the grips (45cm). Body mass and body height were measured on a Kistler force plate (Kistler instrument corp. Amherst, NY, US) and a calibrated stadiometer (Holtain Ltd., Crosswell, UK), respectively.



Fig. 1. Shows simulated double poling seated in custom built sledge.

Test protocols and measurements

Submaximal poling

Submaximal tests were performed in three 4-min sessions. Between the sessions a rest period of 4 min was applied. Initial workrate was adjusted by a subjective fatigue scale ranging from 6-20, where 6 indicates no effort and 20 indicated maximal effort (Borg 1982). The intensity was increased gradually from 10 to 13 to 16 on the Borg scale, which represents submaximal 1 to 3, respectively. Ventilatory parameters along with power per stroke, poling length and cycle rate were continuously measured from start to end in each trial. Poling length was measured by displacement of markers, Cycle rate by the reciprocal of the time used per cycle, and power per stroke by force and velocity during the pull phase. Gross efficiency was calculated as workrate performed by the entire body divided by aerobic metabolic rate. Workrate was calculated as the product of force and velocity using the force cell and motion capture system. Metabolic rate was calculated as the product of VO_2 and oxygen energetic equivalent and processed using a standard conversion table according to Peronnet and colleagues (1991). Since gross efficiency is strongly dependent on workrate, a standardized workrate of 90 W was calculated by linear regression in order to compare skiers within the same workrate.

8-s specific sprint power

After the submaximal poling was finished a rest period of 10 minutes was applied before performing an 8-s specific sprint power test, in which the subjects were instructed to produce as much power as possible. Specific power was calculated as the product of force and velocity, averaged over the period of 8 seconds. This procedure was applied in order to measure specific power and RFD peak. RFD represents the peak of (dF/dt) , whereas RFD_{mean} was calculated as average RFD of all pulls during 8-s sprint period using a differential filter. RFD_{peak} was calculated as the maximal RFD of all pulls during the 8-second period using a differential filter.

VO₂max running

After a 15-minute warm up at 60% of HR_{max}, VO₂max was measured when running on a motorized treadmill according to standardized procedures for testing cross-country skiers in Norway (Ingjer 1991; Sandbakk et al. 2011). The test lasted for 5-6 minutes and was performed at a constant inclination of 10.5% with individual starting speeds and a gradual increase of 1 km·h⁻¹ every minute. The maximal level of effort was considered to be attained when a plateau in VO₂ was achieved, despite increasing intensity and a peak BLa > 8 mmol/L (Basset & Howley, 2000). VO₂, HR, and ventilation were monitored continuously and the averages of three consecutive 10-s intervals with the highest values were used to determine maximal and peak values.

Strength tests

Seated pull-down and pull-over

The seated pull-down was performed on a cable apparatus with standardisation according to Losnegard et al. (2011) (Fig 2). Initially the subjects performed 3 sets of dynamic warm-up at 40, 70 and 80% of estimated 1RM. The load was increased to 2.5 kg below expected 1RM and further increased by 2.5 kg until the subjects failed to lift the load consequently. The same researcher supervised both 1RM tests, and procedures followed the same order in both maximal strength tests. The subjects were also given verbal feedback to encourage good technique in each lift. For the pull-down the bench was positioned perpendicular to the apparatus so that the bar was pulled vertically down to the hip bone. The back was adjusted in an upright position, close to 90 degrees. The subjects strapped their hips to the bench to ensure stability during the lift. Before starting, the participants had to pull the handlebar down to where the straps were perpendicular to the mandible, and the angle between humerus and ulna/radius was 90 degrees. The handlebar had to be pulled down to the hip bone for the lift to be accepted, while keeping the head and back in contact with the bench at all time. For the pull-over exercise, the bench was positioned in the opposite direction, and the back towards the apparatus with the same distance according to the specific seated pull-down (Fig. 3). The back was adjusted to a 45 degree angle, with the same start and stop position according to the pull-down exercise, respectively.

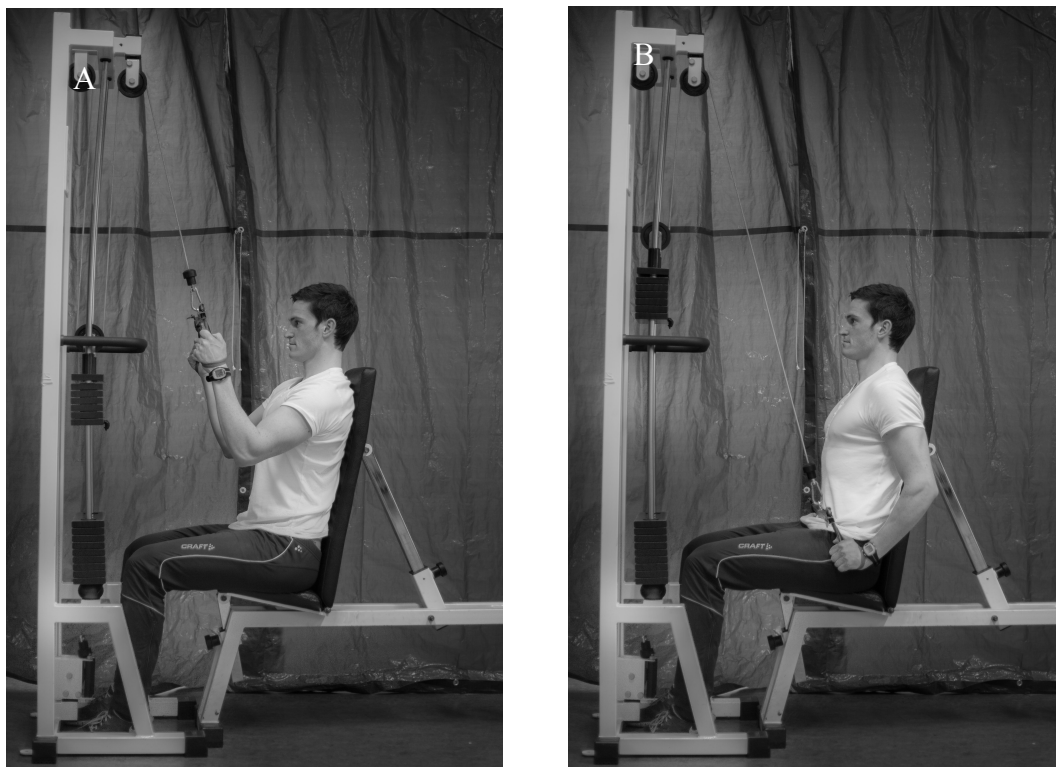


Fig. 2. Showing 1RM pull-down strength exercise performed in a pull-down apparatus. Where (A) indicates starting position, and (B) stop position.

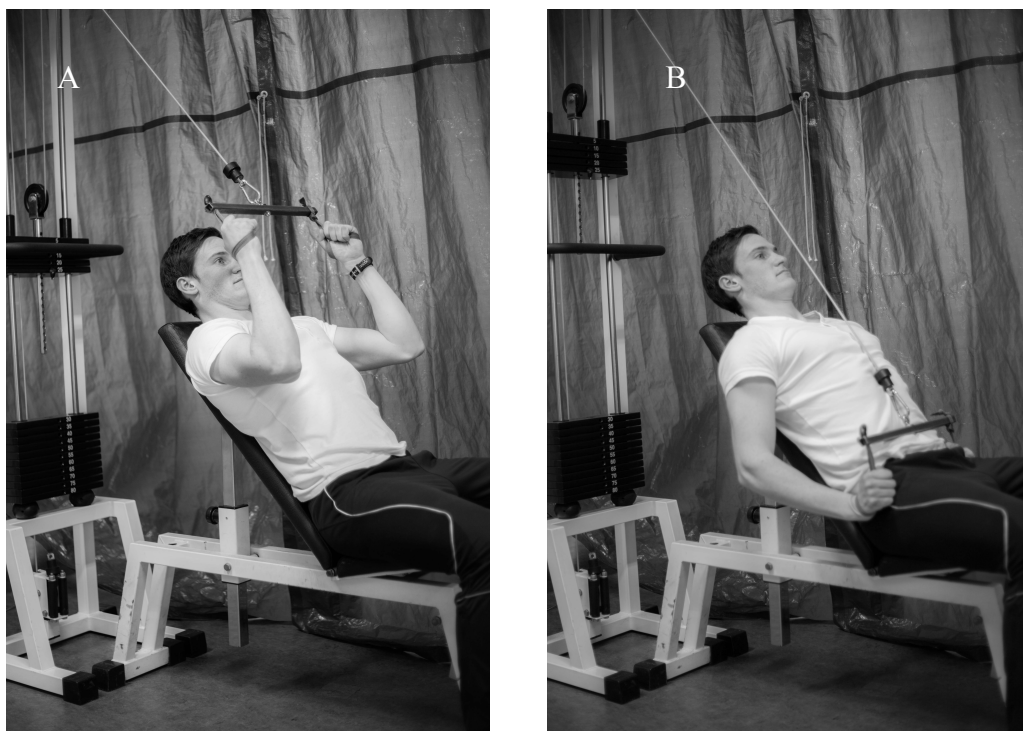


Fig. 3. Showing 1RM pull-over strength exercise in the pull-down apparatus. Where (A) indicates starting position, and (B) stop position.

Statistical Analysis

All data were checked for normality and presented as mean and standard deviation (mean \pm SD). Correlations were analysed using Pearson's correlation coefficient test. One way repeated measures ANOVA was utilized to determine significant difference in variables between submaximal stages. Paired t-test was used to analyse local significant differences between submaximal stages. Statistical significance was set at $P < 0.05$. All statistical tests were processed in using SPSS 11.0 Software for Windows (SPSS Inc., Chicago, IL) and Matlab (The Math- Works Inc., Natick, MA).

Results

Metabolic rate, workrate and gross efficiency

Metabolic rate showed a linear relationship with workrate both on individual basis and for all subjects pooled (Fig. 4a) with an interpolated intercept of 77 W on average at zero workrate. Correlations within each subject were 0.995 ± 0.0005 , where only 4 out of 11 were not significant ($p = 0.05$). Even though these values were based on only three data points each, they indicate that a linear approach for interpolation of gross efficiency at 90 W seems reasonable. Gross efficiency plotted against workrate in Fig 4b, showed an effect of workrate on gross efficiency.

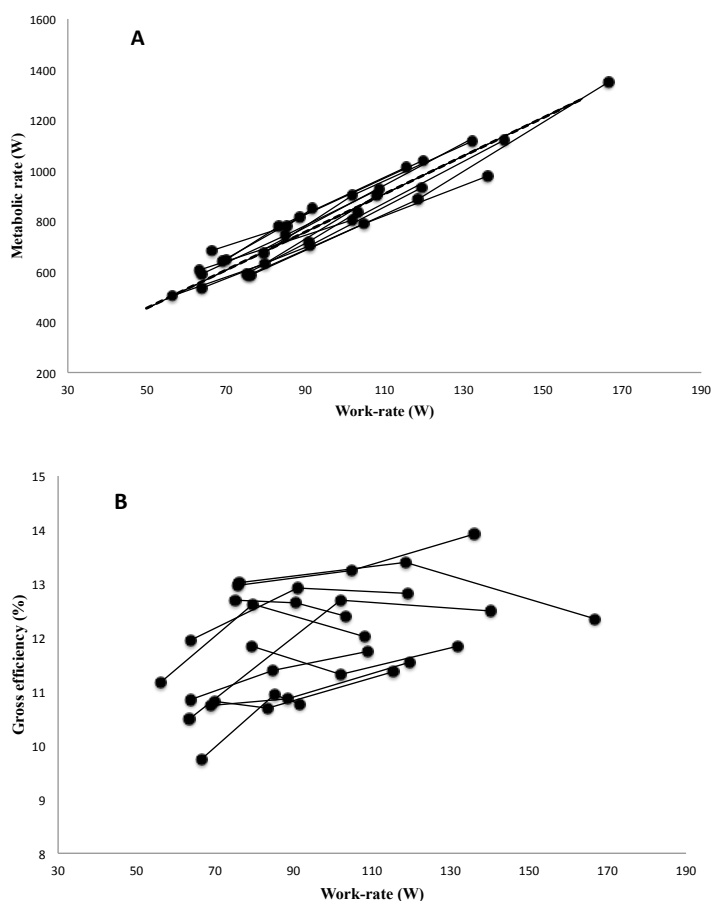


Fig 4. Metabolic rate (A) and gross efficiency (B) correlated against workrate from submaximal stages in double poling ergometer. Trend line (dashed line) is estimated based on linear regression. Each solid line represents one individual for the entire data set.

Physiological correlations

Results from the one way repeated measure ANOVA showed all significant differences ($p < 0.05$) between submaximal stages presented in table 2.

Table 2. Metabolic rate, workrate, gross efficiency, as well as power per stroke, poling length, cycle rate, BLa, VO₂ and RER (respiratory exchange ratio) during submaximal stages presented for 11 cross-country skiers (mean \pm SD)

	Sub-maximal 1	Sub-maximal 2	Sub-maximal 3
Metabolic rate (W)	603 \pm 55	777 \pm 77*	1005 \pm 149 [#]
Work rate (W)	69 \pm 7	93 \pm 11*	121 \pm 20 [#]
Gross efficiency (%)	11.4 \pm 1.0	12.0 \pm 1.0*	12.1 \pm 0.8 [#]
VO ₂ (ml min ⁻¹)	1770 \pm 157	2279 \pm 234*	2924 \pm 435 [#]
RER	0.87 \pm 0.05	0.89 \pm 0.07	0.95 \pm 0.06 [#]
Lactate (mmol L ⁻¹)	1.25 \pm 0.83	1.88 \pm 1.21*	1.84 \pm 1.85 [#]
Power per stroke (W)	132 \pm 13	173 \pm 23*	224 \pm 4 [#]
Poling length (M)	0.95 \pm 0.08	0.99 \pm 0.11*	1.03 \pm 0.10 [#]
Cycle rate (Hz)	0.73 \pm 0.08	0.79 \pm 0.10*	0.85 \pm 0.13 [#]

Significant local differences between previous workrate * $p < 0.05$. Significant local difference between submaximal 1 and submaximal 3 [#] $p < 0.05$.

Correlations between gross efficiency and workrate, power per stroke, poling length and cycle rate are presented in table 3. Power per stroke showed non-significant correlations with gross efficiency in submaximal 1 or submaximal 2, but a significant correlation to gross efficiency in submaximal 3 ($p = 0.03$). Neither cycle rate nor poling length showed significant correlations with gross efficiency in either submaximal stage.

Table 3. The correlations between gross efficiency and workrate, power per stroke (PPS), poling length (PL) and cycle rate (CR) on different submaximal stages for 11 male cross-country skiers. Each mechanical and physiological factor is correlated within the same submaximal stage.

	Sub-maximal 1	Sub-maximal 2	Sub-maximal 3
Work-rate (W)	$r = 0.60, p = 0.05^*$	$r = 0.58, p = 0.06$	$r = 0.50, p = 0.12$
PPS (W)	$r = 0.53, p = 0.09$	$r = 0.51, p = 0.10$	$r = 0.65, p = 0.03^*$
PL (m)	$r = 0.25, p = 0.46$	$r = 0.56, p = 0.51$	$r = 0.34, p = 0.30$
CR (Hz)	$r = 0.08, p = 0.82$	$r = 0.40, p = 0.90$	$r = 0.21, p = 0.54$

* $p < 0.05$

Maximal strength and specific power measurements from the pull down apparatus and 8-s ergometer sprint are presented in table 4.

Table 4. Strength and power characteristics for the elite cross-country skiers involved in the study.

Parameters	Mean \pm SD
1 repetition maximum pull-down (N kg ⁻¹)	38.5 \pm 3.5
1 repetition maximum pull-over (N kg ⁻¹)	37.1 \pm 5.1
Specific power (W)	500 \pm 31.8

Correlations between maximal strength, sprint power and gross efficiency at different submaximal stages are presented in table 5 and figure 5. 1RM pull-down and 1RM pull-over did not correlate with gross efficiency in either submaximal stage. Furthermore, gross efficiency at 90W showed low, non-significant correlations with 1RM pull-down and 1RM pull-over. Maximal strength in pull-down and pull-over showed significant correlations with workrate in submaximal 3 ($r = 0.65$, $p = 0.03$ and $r = 0.65$, $p = 0.03$). RFD_{mean}, and RFD_{peak} were significantly correlated with gross efficiency in submaximal 3 (both $p < 0.05$), but not in Submaximal 1 and 2 or at the interpolated 90W. Specific power showed non-significant correlations with gross efficiency in either submaximal stage. Furthermore, specific power showed significant correlation with workrate in submaximal 3 ($r = 0.63$, $p = 0.04$).

Table 5. The correlations coefficients between gross efficiency at three submaximal workrates and gross efficiency interpolated at 90 W versus 1RM and specific power parameters for 11 male cross-country skiers.

	Sub-maximal 1	Sub-maximal 2	Sub-maximal 3	90W
1RM Pull-down (Kg)	$r = 0.31$, $p = 0.35$	$r = 0.32$, $p = 0.33$	$r = 0.45$, $p = 0.14$	$r = 0.31$, $p = 0.34$
1RM Pull-over (Kg)	$r = 0.37$, $p = 0.26$	$r = 0.33$, $p = 0.31$	$r = 0.32$, $p = 0.30$	$r = 0.37$, $p = 0.30$
Specific power (W)	$r = 0.24$, $p = 0.48$	$r = 0.38$, $p = 0.24$	$r = 0.41$, $p = 0.18$	$r = 0.24$, $p = 0.36$
RFD _{mean} (N/s)	$r = 0.56$, $p = 0.07$	$r = 0.31$, $p = 0.35$	$r = 0.74$, $p = 0.009^*$	$r = 0.46$, $p = 0.15$
RFD _{peak} (N/s)	$r = 0.54$, $p = 0.08$	$r = 0.28$, $p = 0.40$	$r = 0.72$, $p = 0.01^*$	$r = 0.43$, $p = 0.18$

* $p < 0.05$.

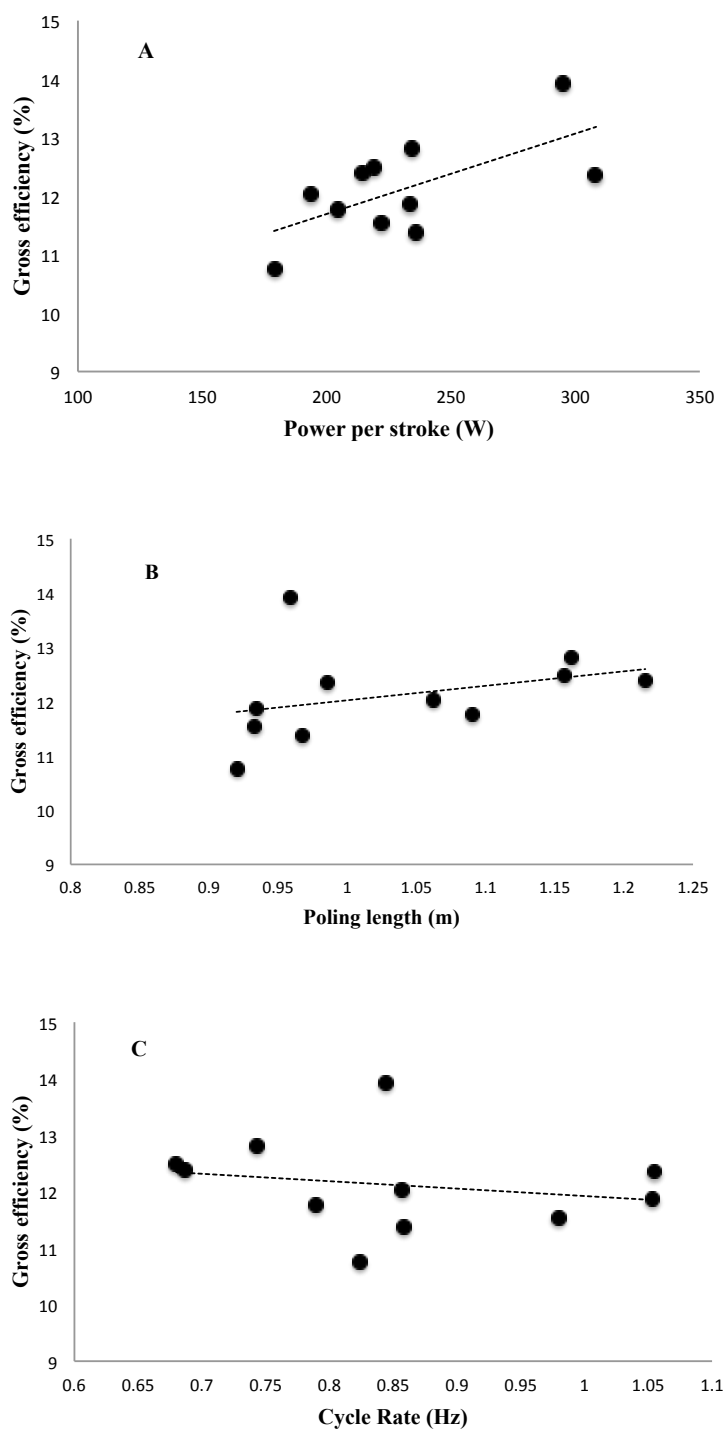


Fig 5. Relationship between gross efficiency and power per stroke (A), poling length (B) and cycle rate (C) in submaximal 3 for 11 male cross-country skiers. Each data point represents one skier and the stapled line representing linear regression line for all subjects pooled.

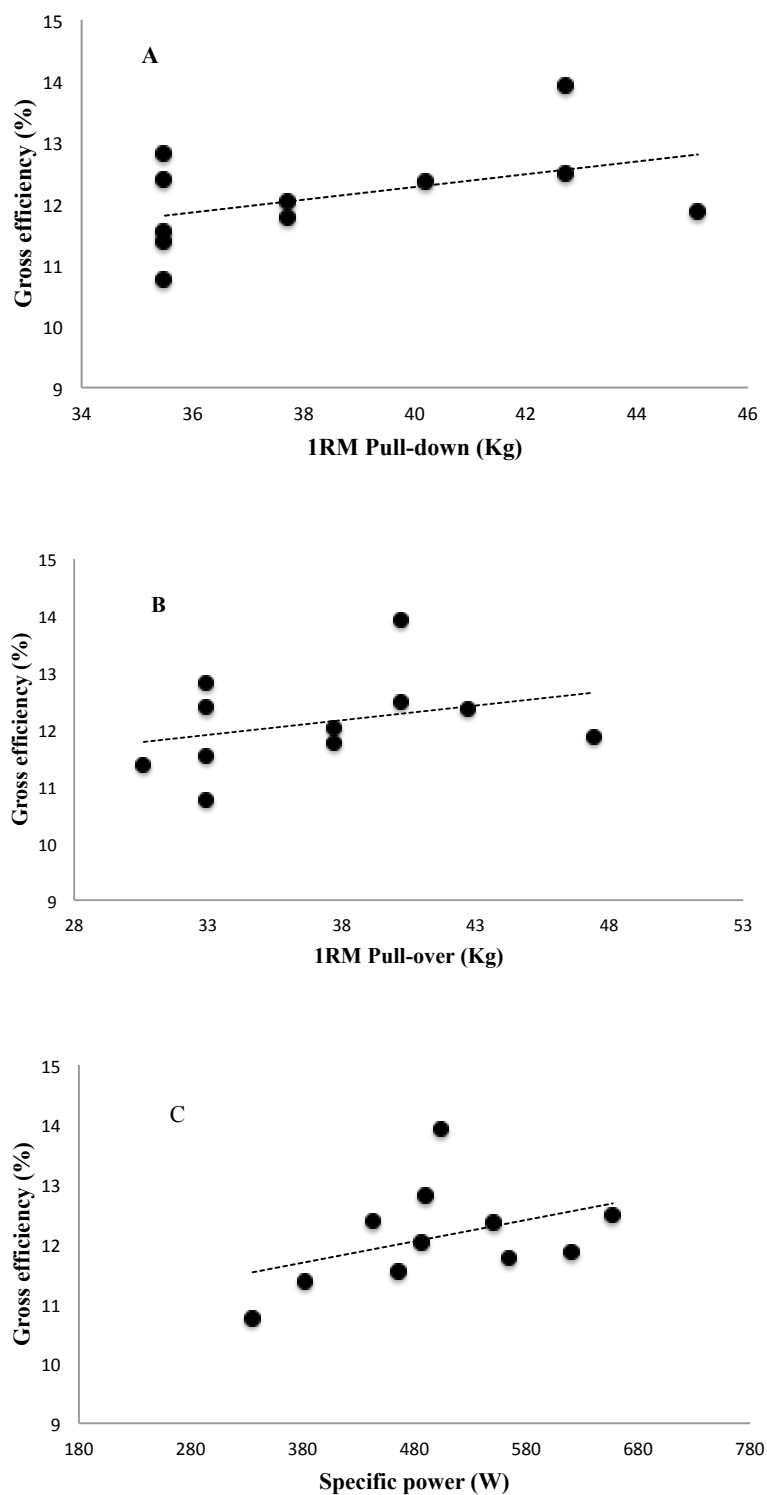


Fig 6. 1RM in two strength exercises (A and B) and 8-sec specific power (C) in relationship to gross efficiency at submaximal 3 for 11 male cross-country skiers. Each data point represents one skier with the stapled line representing linear regression line for all subjects pooled.

Discussion

The current study investigated likely for the first time the influence of upper-body strength and power on submaximal force production and gross efficiency during isolated upper-body poling in cross-country skiers. The main findings were as follows: a linear metabolic workrate relationship was found both within athletes and for all athletes pooled. There was an effect of workrate on gross efficiency between submaximal stages. The higher workrates were associated with an increase in both power per stroke and cycle rate, with power per stroke as the main contributor to enhanced workrates. Within the submaximal stages, power per stroke showed increasing correlations with gross efficiency with increasing workrate, being significant at the highest workrate. Neither 1RM upper-body strength nor 8-s maximal specific power correlated significantly with gross efficiency during submaximal poling. However, there was a tendency towards higher correlations with increasing submaximal workrates, and RFD during the 8-s maximal sprint correlated significantly with gross efficiency at the highest submaximal workrate.

Metabolic rate, workrate and gross efficiency

The present study showed a strong linear relationship between metabolic rate and workrate on individual basis and together pooled. These findings are in accordance with previous studies in cycling and cross-country skiing (Ettema and Loras. 2009; Sandbakk et al. 2010), and are a rather common outcome independent of work type and workrate for both cycling (Moseley et al. 2004; Chavarren & Calbet 1999), and cross-country skiing (Sandbakk et al. 2010; Leirdal et al. 2011; Sandbakk et al. 2012). Overall, these studies together with this one indicate that workrate in isolated upper body poling is similarly related to metabolic rate, as for cross-country skiing and cycling.

The present study found a general effect of workrate on gross efficiency, specifically being a significant increase in gross efficiency from submaximal 1 to submaximal 2, followed by a non-significant increase from submaximal 2 to submaximal 3. This effect can be explained by the decreasing impact of resting metabolic rate on gross efficiency (i.e., the ratio of workrate divided by the total metabolic rate) as presented by Ettema and Loras (2009). These findings are also in accordance to Sandbakk et al. (2010) who showed small increases in gross efficiency at high workrates in roller ski skating. In this context it should be mentioned that

gross efficiency is a measure for efficiency of the entire body as a locomotor system working against environmental resistance, and not a measure for skeletal muscle efficiency i.e., net efficiency (Ettema and Loras. 2009). Gross efficiency measured in this study was within the range of 9-13%, which is somewhat lower compared to other studies done on both roller ski skating (12.5-16.5%) (Sandbakk et al. 2010; Leirdal et al. 2011) and cycling (~20%) (Ettema and Loras 2009). These higher gross efficiencies may largely be explained by the higher workrates (Ettema and Loras 2009). In arm cycling, with lower workrates produced, the gross efficiency is demonstrated to be ~ 8% (Bafghi et al. 2008). Together these aspects may fit the conclusions from cycling showing that about 90 percent of all variance in energy expenditure depends on workrate, and only 10 percent can be explained by other factors such as cadence (Ettema and Loras 2009). In this context, one must also take into consideration the amount of muscle mass activated during the movement. In this study, only the upper body was able to produce external power and was therefore less capable to produce force relative to e.g. cycling and cross-country skiing.

Movement characteristics

The present study revealed simultaneous increases in gross efficiency, power per stroke and cycle rate with the increasing workrate across the submaximal stages. Additionally, the higher power per stroke was followed by slightly longer poling lengths (i.e., longer displacement during the pull phase of each cycle). These findings are in accordance to Sandbakk et al. (2011) who showed similar increases in gross efficiency, power per stroke and cycle rate with increased workrate in roller ski skating. In cross-country skiing, an increase in workrate is characterised by increased forces, and/or increasing cycle rate (Lindinger & Holmberg. 2010; Stöggl et al. 2007; Sandbakk et al. 2010). In the current study there was a significant correlation between gross efficiency and power per stroke at the highest submaximal stage, whereas cycle rate or poling length did not correlate to gross efficiency in either submaximal stage, indicating that increasing cycle rate or applying forces over a longer distance does not enhance efficiency in this locomotion. Based on the characteristics of the ergometer, the ability to increase cycle rate is limited and the key component in increasing workrate is increased power per stroke.

Maximal strength and power

Maximal strength and power are discussed to be of relevance for upper-body work economy in different studies (Stöggl et al. 2009; Hoff et al. 1999) and suggest that a certain amount of strength and power is essential for efficiency and performance in cross-country skiing (Sandbakk et al. 2010; Losnegard et al. 2011). However, in the present study 1RM and maximal sprint power showed low non-significant correlations with gross efficiency. These findings are in line with Sandbakk et al. (2010) who showed no difference in maximal strength between national and international level skiers even though international level skiers had higher gross efficiency. It was discussed that the necessary level of strength may be reached, and that the ability to produce technique-specific power at high speeds was related to submaximal efficiency (Sandbakk et al. 2010). The non-significant correlations found in this study might indicate that maximal strength is not a determining factor for submaximal poling in already highly upper-body trained cross-country skiers. The same can be concluded for the more technique-specific power test, also showing non-significant correlations to gross efficiency. However, there is a tendency towards increasing correlation coefficients with increasing workrates, which might indicate that the ability to produce high maximal power output is of increasing relevance for gross efficiency with increasing workrates. Intensities relative to maximal velocity have shown to correlate strongly with upper body power in an earlier study (Gaskill et al. 1999). In such cases, high maximal strength and power could affect the ability to produce higher workrates and thereby increase gross efficiency. In this study both maximal strength tests correlated significantly with workrate in submaximal 3 which supports this idea.

Significant correlations were shown between RFD_{mean} and RFD_{peak} in submaximal 3 in both cases, where both RFD_{mean} and RFD_{peak} seem to be of increasing importance with increasing workrate. Hoff et al. (1999) showed that time to peak pole force had a positive relationship with work economy in ergometer poling. It has also been demonstrated that RFD is related to velocities relative to a 10-km classic race (Holmberg et al. 2005). Even though the time to produce force does not become the limiting factor during isolated upper body poling, the ability to reach high forces in the early face of the contraction still seems important.

Methodological considerations

The movement characteristics applied in this study are somewhat different from double poling in cross-country skiing. The influence of increased resistance with increasing force is a major discrepancy between regular poling and ergometer poling, and will thereby affect the cycle rate. Thus, one has to be careful when comparing the current findings with those presented in cross-country skiing (Holmberg et al. 2005; Lindinger & Holmberg, 2010). The fact that we used cross-country skiers was because of their familiarity with the movement and the upper body capacity.

Conclusion

The current study revealed a linear relationship between metabolic rate and workrate during submaximal poling. Due to the low workrates produced in isolated upper-body poling, gross efficiency is strongly affected by workrate. During the submaximal stages, both power per stroke and cycle rate increased with workrate, where power per stroke became of increasing importance for gross efficiency with increasing workrates. Maximal strength and sprint power correlated significantly with workrate in submaximal 3, but did not correlate significantly with gross efficiency in any case. Together this indicates that maximal strength and specific power is important for producing high workrates, and that the ability to convert forces into power per stroke during poling determines efficiency.

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