Gross efficiency predicts a 6-min double-poling ergometer performance in recreational cross-country skiers

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Abstract The purpose of the study was to investigate which physiological parameters would most accurately predict a 6-min, all-out, double-poling (DP) performance in recreational cross-country skiers. Twelve male recreational cross-country skiers performed tests consisting of three series lasting 10 s, one lasting 60 s, plus a 6-min, all-out, DP performance test to estimate mean and peak power output. On a separate day, gross mechanical efficiency (GE) was estimated from a 10-min, submaximal, DP test and maximal oxygen consumption ($\text{VO}_2 \text{ max}$) was estimated from an incremental treadmill running test. Power was measured after each stroke from the acceleration and deceleration of the flywheel that induced the friction on the ergometer. The power was shown to the skier on a small computer placed on the ergometer. A multivariable correlation analysis showed that GE most strongly predicted 6-min DP performance ($r = 0.79$) and interestingly, neither DP $\text{VO}_2 \text{ max}$, nor treadmill-running $\text{VO}_2 \text{ max}$, correlated with 6-min DP performance. In conclusion, GE correlated most strongly with 6-min DP performance and GE at the ski ergometer was estimated to be $6.4 \pm 1.1\%$. It is suggested that recreational cross-country skiers focus on skiing technique to improve gross mechanical efficiency during intense DP.

Keywords Ski-ergometer · Cross-country skiing · Double-poling (DP) · Performance · Upper body exercise · Gross mechanical efficiency

1 Introduction

Cross-country skiing is practised on both a recreational and competitive level and has become a popular form of exercise. This is demonstrated by more than 50,000 skiers participating in Vasalop week every year, ranging from recreational to elite skiers. However, skiing on snow is not readily available, and certainly not on a regular basis, to a large percentage of the population having an interest in this form of exercise. Off-season training often occurs on dry land; this sometimes happens on roller skis and different ergometer devices have been developed for dry land use with the intention of simulating this form of exercise [1]. These skiing ergometers are used to simulate cross-country skiing and to train both endurance and high power outputs, and they are also used by athletes from other sports where a considerable work capacity is generated by the upper body (e.g. kayaking, swimming and rowing).

In 1967, Saltin and Åstrand compared the maximal oxygen consumption ($\text{VO}_2 \text{ max}$) among 133 of the best Swedish athletes across 19 different sports—including some who were among the world's best [2]. It was apparent from the study that the athletes with the highest $\text{VO}_2 \text{ max}$ values represented some of the most common endurance sports (i.e. cross-country skiing, running and bicycling). In conjunction with a high anaerobic threshold and well-developed movement economy, these three parameters are often referred to as the essential qualities for an athlete to possess in order to compete among the very best in endurance sports [3–5].

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Several studies have reported that cross-country skiers have extraordinarily high VO_2 max and anaerobic thresholds [2, 6, 7] and found that these parameters, together with movement economy, correlate very well with skiing performance [6, 8]. It is of note that, although they are key determinants for performance, some of the parameters have been found to vary between cross-country skiers at the national and world-class levels [7]. Also, in untrained and recreational athletes, VO_2 max [9], anaerobic threshold [9, 10] and movement economy [11] are also known to determine performance in endurance sports.

Thus, while these three classic factors are key determinants of endurance performance, other physiological properties may influence skiing performance as well, especially in highly technical movements like cross-country skiing. In a group of sub-elite and highly trained recreational cross-country skiers, upper body (UB) peak poling power ($r = 0.94$), and mean 10-s ($r = 0.93$) and 60-s ($r = 0.92$) poling power, all correlated better with race speed in a 10-km classic cross-country ski race than UB maximal oxygen uptake (UB VO_2 peak, $r = 0.88$) [12], indicating that explosive muscle properties (i.e. muscle power) and anaerobic capacity also play important roles in skiing performance. In line with this, training-induced improvements in upper body strength and power, and intense upper body interval training, have repeatedly been demonstrated to improve 3–10-min skiing performance [13–17]. Little is known about predictors of intense skiing performance in recreational cross-country skiers.

The purpose of this study was to investigate predictors for 6-min, all-out, DP performance in recreational cross-country skiers. We hypothesise that gross mechanical efficiency (GE) will be a strong predictor of skiing performance, because it is likely to vary more in a group of recreational skiers than with elite skiers, due to the complex movements required in cross-country skiing. The physiological parameters analysed as predictors of performance are: 10-s DP power, 60-s DP power, GE, DP VO_2 peak and VO_2 max.

2 Methods

2.1 Experimental outline

Figure 1 shows an overview of the study design, which included three separate test days, with several days in between each test day. Two of the test days are identical (days 1 + 2). The first day was used to familiarise the skiers with the procedure and test protocol, and the second day was used for the actual trial. On day 3, two submaximal tests and a maximal treadmill running test for the assessment of VO_2 max were performed.

2.2 Participants

Twelve males participated in this study (age: 30 ± 9 years; height: 181 ± 9 cm; body mass: 81 ± 7 kg). All participants were recreational cross-country skiers with moderate technical skills in the sport. Several of the participants had participated in the Vasaloppet cross-country ski race more than once. Participants provided their informed consent and the study conforms to the Declaration of Helsinki and the ethical guidelines provided by the ethical committee of the Region of Southern Denmark, Denmark.

2.3 Ski ergometer

The ski ergometer used in this study was the air-resistance version of the ThoraxTrainer (ThoraxTrainer, Kokkedal, Denmark), which uses the same friction unit as the Dansprint kayak ergometer (Dansprint ApS, Hvidovre, Denmark). The flywheel is propelled by two ski poles through a string system attached to elastic bands inside the ergometer, and power is then measured directly in the ergometer flywheel. The elastic bands return the poles to their initial position after propulsion. The drag resistance of the ergometer is adjusted by altering the amount of air drawn into the flywheel. The lowest drag level is 1 and the highest is 10. Calibration of the ergometer was performed before each data collection according to the manufacturer guidelines.

2.4 Test procedures

The first two identical test days started with a 5-min warm-up on the ski ergometer. This was followed by a series of all-out DP tests (Fig. 1); three 10-s tests at each drag level [1, 5, and 10, in this study only the tests at drag level 10 were used; (DP10)], one 60-s test at drag level 5 (DP60) and one 6-min test at drag level 1 (DP6). Resting periods between the tests were: 2 min between each of the 10-s tests, 10 min between the last 10-s test and the 60-s test, and 45 min between the 60-s and the 6-min test. The DP10 with the highest mean power output was used for further analysis.

On the third test day, two 10-min submaximal DP tests were performed at drag level 1 in order to calculate the participant's gross mechanical efficiency (GE). The intensity of the two tests was targeted at 60 and 75% of the mean poling power measured during DP6 on day 2, and the participants were instructed to maintain this intensity as precisely as possible. The two tests were separated by only a very short break, during which time data from the ergometer were exported. The two submaximal DP tests were followed by a maximal running test performed on a treadmill (Woodway EXG 70, Waukesha, USA) with the

Fig. 1 Study overview. On days 1 and 2, five all-out double-poling (DP) tests were performed at resistance level (Res) 1 or 5. On day 3, two submaximal tests and a maximal treadmill test for the assessment of VO₂ max were performed

purpose of measuring VO₂ max. In this test, participants ran at 12 km/h starting from a 0% incline with the inclination increasing by 2.5% every 3 min until exhaustion [18].

2.5 Metabolic measurements and estimation of GE

DP6 and the maximal running tests were performed with metabolic measurements [oxygen uptake (VO₂) (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany); heart rate (HR) [Suunto T6c, Finland); blood lactate (BLa) (YSI 1500 Sport Lactate analyser, Yellow Springs Instrument Co., Yellow Springs, OH)] and a subjective rating of perceived exertion (RPE) (6-20 Borg scale). The VO₂ max during DP (DP VO₂ peak) was defined as the highest 30-s mean VO₂ value. The VO₂ max during running was also defined as the highest 30-s mean VO₂ value, and was regarded as valid if two of the following three parameters were met: (i) blood lactate (BLa) was above 8.0 mmol/L, (ii) respiratory exchange ratio (RER) was above 1.10, (iii) rating of perceived exertion (RPE) was 19 or 20. All participants had BLa and RER values above the required values.

VO₂ was also measured during the last 4 min of each 10-min submaximal test. The GE at both intensities was then calculated as

$$GE = 100 \times (P_{\text{ergo}} \times 60) / (20 \times \text{VO}_2) \quad (1)$$

where P_{ergo} is the mean power measured in the ergometer flywheel in the last 4 min of each test and VO₂ is the corresponding mean VO₂ in the same period. Although not

exact, a factor of 20 kJ/L was chosen as mean value corresponding to an RER value of about 0.85, or corresponding to a submaximal intensity of 70–80% VO₂ max. No significant differences were found in GE between the two submaximal tests, and so the GE presented is the mean value of the two tests pooled together.

2.6 Statistical analysis

Statistical significance was accepted at $p < 0.05$. All values are given as mean $\pm$ SD. To determine which parameters best predict 6-min all-out DP performance, a stepwise regression analysis was employed using the mean power output in DP6 from day 2 as the dependent variable. The independent variables and potential parameters predicting performance were as follows: DP10, DP60, DP VO₂ peak (all from day 2), VO₂ max, and GE.

3 Results

3.1 Ski ergometer test performance and VO₂

One participant was excluded from the analysis due to a technical problem during the VO₂ max measurement; hence, data from 11 participants were included in the regression analysis. Performance data from the ski ergometer tests were (in mean $\pm$ SD); DP6 100 $\pm$ 22 watts; DP10 273 $\pm$ 49 watts and DP60 187 $\pm$ 29 watts. The VO₂ max during DP, DP VO₂ peak, was

4226 $\pm$ 572 mL O₂/min and VO₂ max during treadmill running was 4712 $\pm$ 579 mL O₂/min.

3.2 Estimation of gross efficiency

Gross efficiency was calculated from the VO₂ measurements during the last 4 min of each of the 10-min submaximal tests and the P_{ergo} measured directly in the ergometer flywheel, representing the total power to accelerate the fly wheel, excluding power loss from sledge and coil friction, as well as elastic resistance. The mean GE found was 6.4 $\pm$ 1.1%. This GE represents the total skiing ergometer work, excluding power loss from sledge and coil friction and elastic resistance.

3.3 Predictors of 6-min performance

DP10, DP60, and GE all correlated significantly with DP6 ($r = 0.65$, $r = 0.74$, and $r = 0.79$, respectively). There was no significant association between either DP VO₂ peak or VO₂ max (mL/min) and DP6. The best predictor of DP6 was GE, which explained 57% of the variation ($r^2 = 0.57$) in DP6. When VO₂ peak was added to the regression model, it explained 78% ($r^2 = 0.78$) of the variation in DP6.

4 Discussion

The present study evaluated performance predictors for 6-min ski-ergometer DP performance in recreational cross-country skiers. The main study findings were that 6-min all-out DP performance (DP6) was correlated with GE, DP10 and DP60, but not with DP VO₂ peak or VO₂ max.

4.1 Performance predictors

The high correlation between GE and 6-min DP performance was expected because the group investigated consisted of recreational skiers, who are expected to be more heterogenous in terms of skiing technique, and therefore GE, compared with elite cross-country skiers. An interesting result of this study was the absence of correlation between DP VO₂ peak and VO₂ max with DP6. This indicates that some participants were not able to fully utilise VO₂ to generate mechanical work during DP, possibly due to a less skilled DP technique. Moreover, significant correlations are more likely to be found when the variations are large in the independent variables. The between-participant variation in the parameters investigated as performance predictors was the largest for DP60 (56% when expressed as the difference between the highest and lowest values as a percentage of the mean). GE had the

second largest between-participant variation at 54%, and DP VO₂ peak and VO₂ max had smaller variations at 30 and 41%. This might in part explain why DP VO₂ peak and VO₂ max did not correlate with 6-min DP performance.

When compared with other upper and lower body tasks, the variation in GE found in this study and other cross-country skier studies performed on non-elite skiers appears greater. A study involving collegial cross-country skiers found a between-participant difference of 46% [19], which is not far from the variation found in the current group (54%). In runners, the variation in running economy was much lower at 26% for recreational runners and 16% for well-trained runners, respectively [20, 21], and in competitive female rowers, GE was found to be 19.7%, with a between-participant difference reaching 36% (calculated from table and figure data) [22]. The large interindividual variation in GE found in our study population and supported by others may reflect the complexity of the DP movement compared to simpler motor skills like running. Besides GE, DP10 and DP60 were also correlated ($r = 0.53$ and $r = 0.74$) with 6-min DP performance, which agrees with findings from Alsobrook and Heil showing that UB performance in 10- and 60-s maximal tests correlated more strongly with performance in a 10-km mass-start cross-country race than DP VO₂ peak [12], proposing that the stronger correlations were likely due to underlying relationships between 10- and 60-s performance with GE. In this study, we did not find any such relationship between either DP10 ($r = 0.15$) or DP60 ($r = 0.43$, $p = 0.09$) and GE. However, numerous training studies support the notion of UB performance as a better predictor of performance than VO₂ peak. Thus, 9 weeks of explosive strength training in a group of relatively well-trained runners significantly improved running economy, which was presumed to result from neuromuscular changes [23], and similar findings were reported in a group of male cross-country skiers following 8 weeks of high intensity pulley-resistance training [13]. In the latter study, the authors put forward that the rate of force development and muscle power might be more important factors in improving movement economy than maximal strength itself, with better blood flow and lactate clearance within active muscles being underlying mechanisms that potentially explain the effect of resistance training [13].

4.2 Gross efficiency in the ski ergometer

The mean participant GE found was 6.4 $\pm$ 1.1%, which indicates a considerable power loss to the recoil system and/or friction compared to studies using other ergometer types. In a study using a Concept2 Ski ergometer (Morrisville, VT, USA), power was calculated directly in the flywheel, but using direct transformation by hands to the strings [24]. In that study, GE could be estimated from Fig. 5 to be 12%, which is still low but closer to Ainegren

et al., who calculated efficiency to be between 11.1 and 13.4% in diagonal skiing on a treadmill [25]. The deviation between the power measured using our ski ergometer adapted from kayaking and the GE measured on a treadmill or snow is consistent with the deviation in power reported by Holmberg and Nilsson using a ski ergometer adapted from rowing [1]. Thus, the efficiency in an ergometer could also be expressed including the aforementioned power loss from sledge friction, coil friction and elastic resistance, thereby increasing the value for efficiency. These findings suggest that when such ski ergometers are used in testing situations, a prior validation study is required to establish the relationship between ergometer-measured power and pole power for precise quantification of performance.

5 Conclusion

The main findings of this study were that GE correlated most strongly with 6-min DP performance and that neither DP VO_2 peak nor VO_2 max correlated with 6-min DP performance. The present findings suggest that moderately trained cross-country skiers should focus on improving their technique to increase their DP gross mechanical efficiency rather than their maximal oxygen uptake, if the intention is to improve DP cross-country skiing performance.

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