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ORIGINAL ARTICLE

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Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans

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Abstract Maximal strength-training with an emphasis on maximal mobilization during cross-country skiing increases exercise economy when double-poling. The aim of this experiment was to investigate whether the mechanism of this increase is a change in the force-velocity relationship and the mechanical power output. A group of 19 cross-country skiers having an average peak oxygen uptake of 255 $\text{ml}\cdot\text{kg}^{-0.67}$ body $\text{mass}\cdot\text{min}^{-1}$ or 61 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ were randomly assigned to either a high resistance-training group ($n=10$) or a control group ($n=9$). Upper body endurance was tested on a ski ergometer. The high-resistance-training group trained for 15 min on three occasions a week for 9 weeks. Training consisted of three series of five repetitions using 85% of one repetition maximum (1RM), with emphasis on high velocity in the concentric part of the movement. Upper body exercise economy, 1RM and time to exhaustion increased significantly in the high resistance-training group, but was unchanged in the control group. Peak power and the velocities for a given load increased significantly, except for the two lowest loads. We conclude that the increased exercise economy after a period of upper body high resistance-training can be partly explained by a specific change in the force-velocity relationship and the mechanical power output.

Keywords Power · Cross-country skiing · Neural adaptations · Exercise economy · Peak oxygen uptake · Maximal strength-training

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Introduction

Endurance is the ability to perform large-muscle, whole-body exercise at moderate to high intensities for extended periods of time (Saltin 1973). Endurance in cross-country ski competitions, lasting 10–120 min, is 85%–99% dependent on aerobic metabolism (Åstrand and Rodahl 1986; Bergh et al. 1991). Most previous work regards the maximal oxygen uptake ($\dot{V}O_{2max}$) as the single best indicator of the cardiorespiratory endurance capacity of an individual (Ingjer 1991). The concepts of anaerobic threshold (Th_{an}) and exercise economy (C) also have to be used to predict performance in an endurance event (Costill et al. 1973; Pate and Kriska 1984). The Th_{an} is defined as the intensity of exercise or oxygen uptake ($\dot{V}O_2$) at which the appearance of lactate in, and its disappearance from, blood are equal (Helgerud 1996). Gross $\dot{V}O_2$ at a standard submaximal exercise intensity reflects C . These three key determinants of aerobic endurance, $\dot{V}O_{2max}$, Th_{an} and C, enable the effectiveness of endurance-training procedures to be ascertained. Peak oxygen uptake ($\dot{V}O_{2,peak}$) during exercise using an arm and shoulder ergometer is limited by the relatively small muscle mass involved, restricted capillary density, shorter mean time the blood needs to pass through the capillaries (mean transit time) and the smaller oxidative capacity of the muscles (Shepard et al. 1988).

The highest power is attained when the velocity of contraction is 25%–30% of the maximal value; the force is then close to 30% of the maximal isometric strength (Moritani et al. 1987), though very few studies of training in this area have been reported. Kaneko et al. (1983) found significant improvements in the trained part of the force-velocity curve and corresponding changes in the mechanical power output as a result of muscle power-training. An increased muscle strength can be explained by two separate mechanisms, muscle hypertrophy and neural adaptations. To train the fastest motor units, which develop the highest force, it is necessary to work against high loads (85%–95% of one repetition maximum, 1RM).

Maximal advantage will be gained if the movements are made with a rapid action, in addition to the high resistance (Moritani 1992; Hoff and Almåsbakk 1995). As a method for increasing the rate of force development, which is mainly based on neural adaptations, dynamic movements with a few repetitions (3–7) with explosive movements are required (Schmidtbleicher 1992). This may result in neuromuscular adaptation with only a small amount of hypertrophy (Almåsbakk and Hoff 1996). The ability to develop force rapidly might be an important factor in successful cross-country skiing. The increases in time to exhaustion (mean 7 min) during endurance events correlate with increased rate of force development (Hoff et al. 1999). Training responses may be specific to the joint angle at which training occurs, an indication that neural adaptations may play an important role in the response to strength-training (Sale 1992). However, Hoff and Almåsbakk (1995) raise critical questions about this, suggesting testing of maximal strength (1RM) and maximal rate of force development in evaluating the parameters of strength tests.

In several sports, an increased body mass as a result of muscle hypertrophy is not desirable as the athlete would have to transport this greater body mass. In addition, an increased muscle mass does not necessarily increase maximal strength (Tesch and Larsson 1982). In addition to muscle hypertrophy, maximal strength can be increased by adaptation of the nervous system to the training stimulus. The term ‘‘neural adaptation’’ is a broad description involving a number of factors, such as selective activation of motor units, synchronization, selective activation of muscles, ballistic contractions, increased rate coding (frequency), increased reflex potential, increased recruitment of motor units and increased co-contractions of antagonists (Behm 1995). During the first weeks of a high resistance-training programme an increased 1RM is observed, without any changes in the cross-sectional area of the muscle. This may be due to neural adaptations (MacDougall 1992; Behm 1995), though development of movement coordination plays an important role in velocity -specific gains in strength (Almåsbakk and Hoff 1996).

Hickson et al. (1980, 1988) concluded that performance is not influenced if high-resistance strength-training is added to ongoing endurance-training regimes. A corresponding study using a cycle ergometer showed that the increased strength possibly results in increased participation of slow-twitch fibres and a reduced rate of fast-twitch fibre recruitment with each pedal thrust during exercise against a standardized submaximal load (Gollnick et al. 1974). Helgerud and Wisløff (1998), Wisløff and Helgerud (1998) and Hoff et al. (1999) suggested that increased endurance may occur as a result of increased *C* after a period of maximal strength-training in endurance-trained athletes, and not from changes in $\dot{V}O_{2max}$ or Th_{an}. The strength-training was performed to emphasize neural adaptations, accompanied by small amounts of, or no muscle hypertrophy. They reported a significantly increased time to exhaustion on a ski ergometer as a result of improved *C*, without changes in the frequency of double-poling. They also reported that an increased peak force and time to peak force were found when 1RM tests were used. Wisløff and Helgerud (1998) reported that time to exhaustion was increased by 79.5% among medium-trained women, which indicated that the degree of benefit may have been due to the level of fitness. Small increases in force and velocity may result in a relatively large increase in power (Saltin 1973).

Although the ability to perform well using both muscle power and endurance is important in a variety of sports, the literature does not give much insight into how the fundamentally different properties affect one another. Based on the reported information, increased *C* in the upper body of male cross-country skiers occurs as a result of the increases in the 1RM tests achieved in high resistance-training, emphasizing the neural adaptations. The hypotheses in the present experiment was that increases in the 1RM test would improve *C* economy, due to an increased peak power and a shift in the power-curve in the force-velocity relationship.

Methods

Subjects

A group of 19 highly trained male cross-country skiers were selected for this experiment. The criteria for participation in the experiment were an upper body $\dot{V}O_{2,peak}$ of at least 55 ml·kg^{-1} body mass·min^{-1}, together with having been an active competition racer in cross-country skiing for at least 5 years. After being informed of the procedures, methods and possible risks involved, each subject reviewed and signed a consent form which had been approved by the Human Review Committee prior to participating in the study. The subjects were randomly assigned to one of two groups. There were 10 subjects who took part in the high resistance-training, while 9 subjects comprised the control group. The average of the subjects' physical and physiological characteristics before the training period are presented in Table 1.

Experiment procedure

The experiment and the control group completed a 1 day test procedure before and after the experiment. The subjects were informed beforehand about the length of the study and which test parameters would be used. They were asked not to undertake strength-training during the 2 days before the experiments, to avoid the influence of non-restituted musculature.

Procedure for spirometry tests

The Erich Jaeger Flowscreen (Germany) employing automatic calibration was used to determine vital capacity and forced expiratory flow (Flowscreen Instruction Manual 1991).

Procedure for haemoglobin determination

The Reflotron (Mannheim Boehringer) reflectometer was used for analysis of whole blood. The apparatus was calibrated using a Reflotron check strip, which controlled the optical system in the Reflotron (Reflotron Instruction Manual).

Table 1 Physical and physiological characteristics of the subjects

Variables	Experiment group		Control group	
	($n = 10$)		($n = 9$)	
	Mean	SD	Mean	SD
Age (year)	21.0	1.6	24.4	5.0
Height (cm)	182	2.8	180	3.8
Mass (kg)	77.8	4.9	74.0	3.5
Haemoglobin ($g \cdot dl^{-1}$)	14.9	0.5	14.9	0.7
Haematocrit (%)	44.0	1.0	43.9	1.8
Vital capacity (l)	5.71	0.55	5.65	0.63
Forced expiratory flow in 1 s (%)	81.6	3.3	81.7	4.8
Peak heart rate ($beats \cdot min^{-1}$)	190.0	10.1	190.0	11.6

Procedure for strength tests using the modified pull-down apparatus

This apparatus included a modified latissmus pull-down apparatus (Fig. 1), using which the subjects performed a simulated double-poled pull-down, sitting on a bench provided with a locking mechanism over their thighs (Eleiko Sport, Sweden). The parameters were measured using a force transducer (weight tolerance given as ± 1%), attached between the ropes to the weights and the grip used by the subjects. The force transducer (Transducers, model 363-D3–0. 5T-20PI, USA) was coupled to a computer (Olivetti 6440, Compaq 171 FS screen), which registered and treated the data.

To examine the movements of the weights on the latissmus pull-down apparatus, a position measurement device was used (Houston Scientific, model 1850–040, USA). This was placed at the same level as the starting level of the weights on the apparatus. The position measurement device was connected to the weights, which pulled the string connected to the position measurement device. This method made it possible to measure the movements on the weights throughout the pull-down.

Before using the pull-down apparatus a standard two-part warming-up procedure was employed; a general part – 10 min of treadmill running (Challenger 5.0) at 50% of $\dot{V}O_{2max}$, and a specific part – ten repetitions of approximately 50% of 1RM on the pull-down apparatus.

The subjects completed the modified pull-down sitting on a bench, 2 m from the apparatus, with a locking mechanism over their thighs. Before the test started, the weights were lifted until they made no contact with the ground. Then the subjects grasped the rope with their arms completely extended at shoulder level. This procedure avoided the subjects having to make an eccentric contraction at the beginning of the movements. To make a connection with the movements on the ski ergometer, the criteria for the modified pull-down being accepted was that the processus styloideus ulnae should reach the trochanter major at the hip. During the last part of the pull-down the elbow joint should be extended more than 90° to be accepted. The pull-down movement was carried out during a continuous range of motion.

The subjects in the training group started at a load at 9 kg. Each subject made three repetitions using each load, there being a standard rest of 30 s between each one. The load was increased in 3 kg steps, until the criteria for the pull-down could no longer be achieved. The last load was taken as the highest that the subjects were able to complete 1RM. The other 9 subjects started with 1RM, and went on with 3 kg less on every step. On the last step, the weights on the apparatus were locked, in order to get an isometric measurement.

Procedure for estimating Th_{an} *during double-poling and* $\dot{V}O_{2,peak}$

The $\dot{V}O_2$ was measured using a gas analyser (Jaeger EOS – Sprint, GmbH, Würzburg, Germany). During the measurements the subjects wore a noseclip, so as to breathe through the mouth only. The expired gas was collected in a PVC bag and was automatically analysed every 30 s. The results were registered graphically and numerically by computer (Compac Descpro 286e). The $\dot{V}O_2$ measurements had an accuracy of about ± 3% of the measured results (MacDougall1992).

The ski ergometer (Fig. 2; Cross-country Ski-simulator, Helgerud and Rasmussen, Trondheim) consisted of a steel frame having a rolling belt on which the subjects stood. There was also a pair of ski poles running in guide rails. A line was fastened to the ski poles. This line was connected by wires to an electric motor (Elektri 0.75 Kw, Sg 80-4B, Norway) at the front of the ergometer. There was a system of springs above the motor, which turned on the motor drum when the poles were pushed backwards thereby

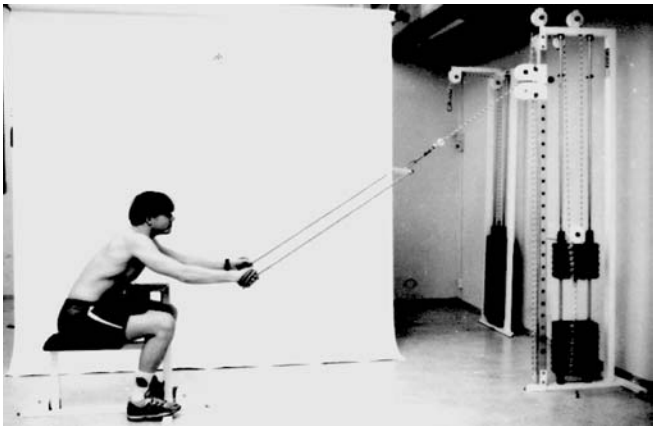

Fig. 1 The modified pull-down apparatus

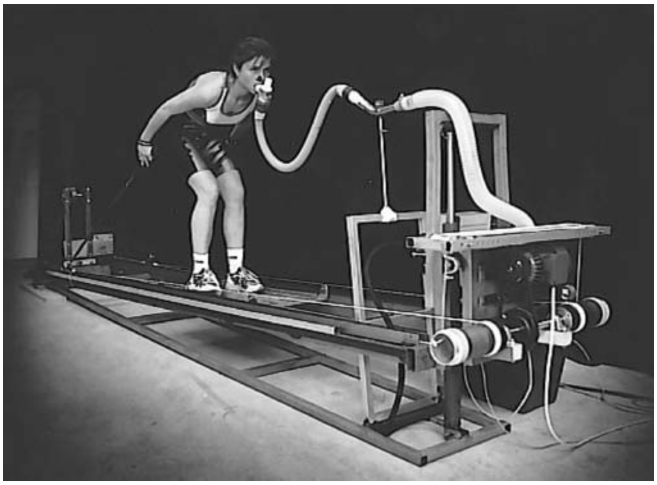

Fig. 2 The ski ergometer

facilitating the forward movement of the poles. The ergometer had a changeable inclination; we used 5°. The power was regulated by changing the velocity on the motor via a computer (Olivetti M300). The power output has been expressed in watts, calculated from the equation:

$$\text{Poweroutput(W)} = \sin\alpha \cdot m_b \cdot v \quad (1)$$

where m_b is the body mass in Newtons, v is the motor speed in metres per second and α is the inclination of the ski ergometer. The poles were braked by the motor when poling speed exceeded the motor speed; as a result, power was developed and the platform was accelerated. The power output was registered by a load cell (Tefka 250 kg, 1.8 mv·v^{-1}, Denmark). The load cell was linear from 0 to 250 kg, and its reproducibility was 0.1% (ScanSence AS 1991). The load cell was coupled to the computer, which also registered and treated the data from the ski ergometer (Cross-country Ski-simulator, Arntzen 1995, Trondheim). A study of Wisløff and Helgerud (1998) showed the ski ergometer to be both reliable and valid for evaluating $\dot{V}O_2$ and force development in the upper body at submaximal and maximal exercise intensities in cross-country skiers.

A graded protocol was used in determining the Th_{an} during double-poling ($Th_{an,dp}$). After a warm-up period of 10 min at an intensity which was stipulated to be 50% of $\dot{V}O_{2,peak}$, the subjects double-poled for 5 min at three to four different speeds (intensities from 60% to 95% of %Vitdot;$O_{2,peak}$), with a 30 s break for determining the blood lactate concentration ($[La^-]_b$) until the $Th_{an,dp}$ was reached. The $[La^-]_b$, unhaemolyzed, was measured using a YSI model 1500 Sport Lactate Analyser (Yellow Springs Instruments Co., USA). The analyser is reported to be linear in the range 0–15 mmol·l^{-1}. In cases where lactic acid concentrations were between 0 to 10 mmol·l^{-1} a common estimate standard deviation was 0.1 mmol·l^{-1}. With concentrations between 10 to 20 mmol·l^{-1}, the estimated standard deviation was 0.2 mmol·l^{-1} (YSI Instruction Manual 1994). Heart rate (f_c) was measured using short-range radio telemetry (Polar Sport Tester, Polar, Finland). A belt holding two electrodes was fastened to the chest of the subjects. The electrodes registered f_c as a mean of 5 s intervals.

Wisløff and Helgerud (1998) found that the $Th_{an,dp}$ was reached at a power output ($\dot{V}O_2$, or f_c), which gave on average a mean $[La^-]_b$ of 1.8 mmol·l^{-1}, independent of whether a 3 or 5 min or 20 min exercise stage was used. Therefore, in this experiment, the $Th_{an,dp}$ was defined as 1.8 mmol·l^{-1} + $[La^-]_b$ values after the warm-up period. When the $Th_{an,dp}$ was reached, the intensity was increased by 20 W every 30 s until $\dot{V}O_{2,peak}$ was reached. Wisløff and Helgerud (1998) recommended a 5° inclination.

Procedure for the test to exhaustion using the ski ergometer (5° inclination)

The subjects warmed up for 10 min by running on the treadmill. They then double-poled for 10 min on the ski ergometer at an intensity of about 50% of $\dot{V}O_{2,peak}$, after which the speed was increased every minute to give an increase in power output of 30 W up to the speed which gave the power output (in watts) at which they had reached the $\dot{V}O_{2,peak}$ in the earlier test. Measurements then began and the test finished when the athlete could not keep ahead of a given mark on the ski ergometer.

To compare the C during double-poling (C_{dp}) from pre- to post-test, the C_{dp} at post-test was calculated at the same power output as in the pretest, although this was no longer the exact $Th_{an,dp}$. To be able to convert the total force developed into the force exerted through the ski poles while double-poling, a video camera was used. By combining a screen picture of the force developed with the actual double-poling movements, it was possible to determine at which pole angle peak force was developed. From the equation:

$$F_1 = F_2 \times \cos\alpha \quad (2)$$

where F_1 was the measured force using the ski ergometer and α was the angle between the ski poles and the steel-frame of the ski ergometer, the average peak force (F_2) was calculated.

Training

The experiment period extended over 9 weeks, and was carried out in the autumn before the start of the season of cross-country competition. Because of the reported increase in both 1RM tests and time to peak force (Schmidtbleicher 1992; Hoff and Almåsbakk 1995), emphasis was put on mobilization during the concentric part of the pull-down. For the experiment group, approximately 45 min a week out of a total training-time of approximately 15 h a week were used to carry out modified pull-downs, starting with approximately 85% of 1RM in six repetitions and three series per training session. The rest interval was 2–3 min. When a subject successfully executed six repetitions in three series, the load was increased by 3 kg for the next training session. To avoid a treatment effect on performance, the training sessions were monitored only three times throughout the experiment period by the investigator, but every week by their trainers. The strength-training performed by the control group was limited to the traditional "strength endurance"-training, with an intensity of less than 85% of 1RM. Each subject kept a record of his training throughout the period of the experiment.

Statistical analyses

The statistical analysis was performed using the commercial software package SPSS for Windows (release 7.5.1, SPSS Inc., Chicago, Ill.). Prior to choosing the method of statistical analysis, the Kruskal-Wallis test-statistic was calculated for all data sets, to check that the observed data came from a normally distributed population. From these results it was decided to use parametric methods. Analyses of variance (ANOVA repeated measurements) were used to determine significant differences between the various tests and the two groups. Differences within the groups from pre- to post-test were analysed using one-tailed paired-sample Student's t-tests. Differences between the groups were analysed using one-tailed independent-sample t-tests in the cases where there was a significant difference from pre- to post-tests in both groups. The variances between the two groups in this study were considered in the interpretation of the statistics calculated in the two tests. A significance level of 0.05 was considered to be statistically valid. The results are given as mean (SD).

Results

In the experiment group, the velocities achieved using a given load increased significantly ($P < 0.01$) after training in all load conditions except the two lowest (Fig. 3). Similarly, the peak power increased significantly ($P < 0.01$) using every load except the two lowest. There were no significant changes in the control group. The mean values of force, velocity and powerobtained in the pre- and post-training tests in the experiment group are shown.

The mean values of the results obtained in the pre- and post-training tests in the experiment group are given in Table 2 and 3 with standard deviations. Peak powers as percentages of the maximal isometric force were calculated on the basis of the subjects' average values. Both in pre- and post-tests it was on average 47%. A shift of the convex force-power curve was found.

Time to exhaustion increased significantly in the experiment group from the pre- to post-test. The $[La^-]_b$ after the test to exhaustion did not change significantly in any of the groups. Furthermore, the subjects in the experiment group showed a significant ($P < 0.05$)

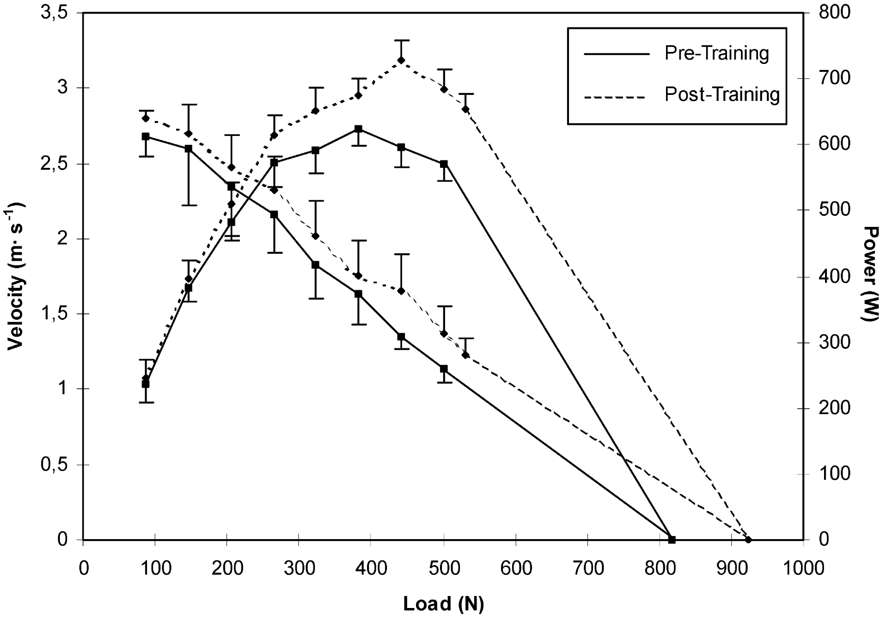

Fig. 3 Mean (SD) changes in the force-velocity (almost linear) and force-power (inverted U-shaped) relationships following training. Power is the product of load and velocity

Table 2 Results from the one repetition maximum (1RM) tests and time to exhaustion on the ski ergometer before and after 9 weeks of training. $[La^{-}]_b$ Blood lactate concentration, m_b, body mass

Variables	Experiment group ($n=10$)				Control group ($n=9$)			
	Before		After 9 weeks		Before		After 9 weeks	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Time to exhaustion (min)	5.26	1.90	8.47	3.36	4.84	1.66	5.15	1.51
$[La^{-}]_b$ (mmol·l^{-1})	7.2	0.7	7.7	1.1	6.9	1.2	7.4	1.3
1RM (kg)	43.8	3.8	53.4	3.4	43.7	5.0	44.2	5.6
Relative strength (1RM·$m_b^{-0.67}$) (kg)	2.37	0.15	2.88	0.15	2.43	0.22	2.47	0.27

increase in the 1RM test and a significant ($P<0.001$) increase in relative strength, while the results from the control group did not change significantly.

The $\dot{V}O_{2,\mathrm{peak}}$ and Th_{an} during double-poling did not change significantly from pre- to post-test in any of the groups.

In the experiment group but not in the control group, the C_{dp} was significantly increased from pre- to post-test ($P<0.01$). There were no significant differences in C_{dp} during three submaximal steps during double-poling in either of the groups. There were no significant differences in poling frequency on the ski ergometer, either from the pre- to post-test or during three submaximal steps. In Fig. 4 the distribution of the different methods of training of the athletes is shown. Table 4 shows the type of activity during the period of the experiment. The experiment group trained 14 (2.4) h a week, while the control group trained 12 (2.7) h a week.

In both groups approximately 80% of the total time was spent on endurance-training. On average, the experiment group performed approximately 75% of the prescribed high resistance strength-training sessions, which implied an average of 30 min of this type of training a week. Both groups of subjects continued their normal endurance-training.

Peak force was developed at an average 46° ski-pole angle when double-poling. The average peak force (F_2) through the ski poles was 113.7 (8.7) N. This force was equivalent to 25.9% and 21.1% of maximal dynamic force (1RM) developed using the modified pull-down apparatus in the pre- and post-tests, respectively.

Discussion

In the experiment group, specific training effects on the force-velocity relationship and the mechanical power output occurred after training at 85% of 1RM with an emphasis on maximal mobilization. Power production significantly increased in the experiment group from the pre- to post-tests, and a shift of the convex force-power curve was found. There were significant increases in movement velocity in the experiment group from pre- to post-tests using the pull-down apparatus, except at the lowest loads. The results show that a relatively small change in 1RM had a substantial effect upon endurance, expressed as time to exhaustion on the ski ergometer. The training for an enhanced 1RM, emphasizing neural adaptations, led to significant changes in rate of force development using the pull-down apparatus. These

Table 3 Exercise economy during double-poling (C_{dp}), anaerobic threshold during double-poling ($Th_{an,dp}$) and peak oxygen uptake ($\dot{V}O_{2,peak}$) before and after 9 weeks of training $f_{c,peak}$ Peak heart rate, m_b body mass (kg)

Variables	Experiment group ($n=10$)				Control group ($n=9$)			
	Before		After 9 weeks		Before		After 9 weeks	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C_{dp} (ml·kg$^{-0.67}$·m^{-1})	1.13	0.06	1.03	0.06	1.11	0.15	1.14	014
$\dot{V}O_{2,peak}$[a]								
(l·min^{-1})	4.89	0.60	4.82	0.56	4.39	0.35	4.54	0.33
(ml·m_b^{-1}·min^{-1})	63.1	5.8	61.8	4.3	59.2	2.8	61.4	3.0
(ml·$m_b^{-0.67}$·min^{-1})	265.3	25.9	260.6	21.8	245.1	13.4	254.3	13.7
$Th_{an,dp}$[a]								
(l·min^{-1})	3.87	0.51	4.03	0.60	3.46	0.37	3.52	0.34
(ml·m_b^{-1}·min^{-1})	49.8	6.6	51.6	7.7	46.7	5.0	47.6	4.6
(ml·$m_b^{-0.67}$·min^{-1})	209.6	29.1	218.0	29.0	193.0	19.6	196.9	17.5
(% of $\dot{V}O_{2,peak}$)	79.2	4.1	82.9	5.1	77.1	5.3	79.0	6.0
(% of $f_{c,peak}$)	88.9	5.4	88.8	4.3	88.2	6.6	88.5	4.4

[a] Inclination of the ski ergometer 5°

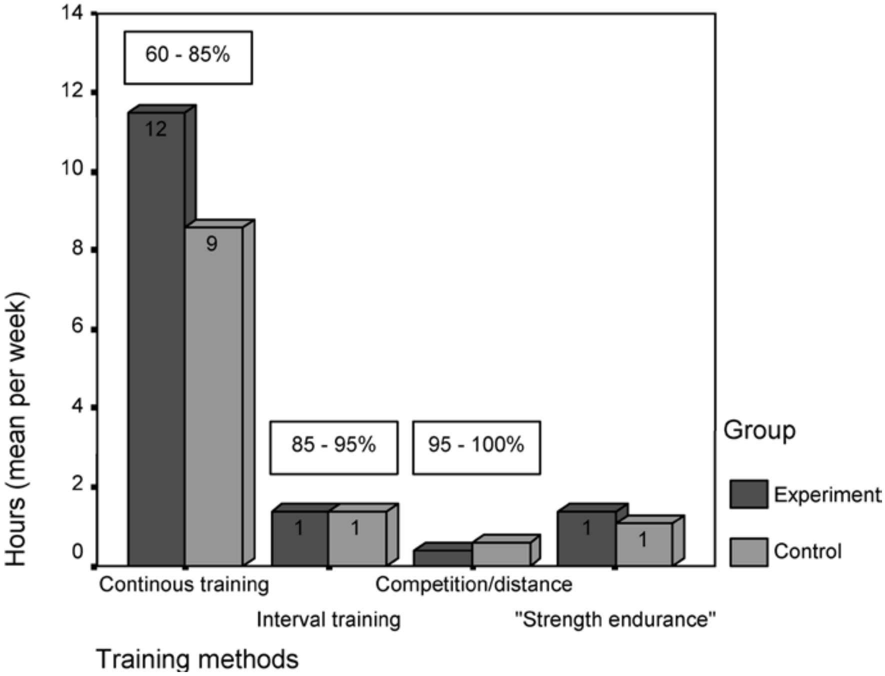

Fig. 4 Summary of the training methods of the two groups during the experiment. The training methods are given in hours per week of training at the percentages of the peak heart rate shown. *"Strength endurance"* indicates workout periods of approximately 1 min, corresponding to 50%–60% of one repetition maximum

Table 4 Summary of the types of activity of the groups in hours (mean per week)

Variables	Experiment group ($n=10$)		Control group ($n=9$)		Difference between the experiment and the control group	
	Mean	SD	Mean	SD	Mean	SD
Roller skis	3.9	1.3	3.8	1.5	0.1	0.2
Cross-country skiing	1.1	1.0	0.3	0.4	0.8	0.6
Running	7.8	1.5	6.4	0.8	1.4	0.7
Other training	1.9	0.6	1.3	0.7	0.6	0.1

results may indicate that it is the increases in rate of force development and thus power production, rather than the increased 1RM per se that alters endurance. On the other hand, as 1RM increased by 20.9% in the experiment group compared to the control group, the load relative to the subject's 1RM at which the subjects exercised during the test of time to exhaustion decreased. Thus, a possible alternative explanation might be that the experiment group after the training period increased their C due to a relatively lower intensity.

Time to exhaustion increased significantly, by as much as 55%, in the experiment group, compared to the control group from pre- to post-test. This is in line with the results of Wisløff and Helgerud (1998) who reported that time to exhaustion had increased by 79.5% compared to the control group on the ski ergometer among trained women, after a period of high-resistance strength-training. In their training regimen they also emphasized maximal mobilization or maximal intended velocity, a regimen similar to that in this experiment. Double-poling at the standardized exercise intensity in the pre- and post-tests induced a 9% and significantly increased C_{dp} in the experiment group. As the relative exercise intensity was reduced, this induced a considerably longer time to exhaustion at maximal aerobic velocity. Endurance time is a function of the relative exercise intensity and increases exponentially with decreasing relative exercise intensities (Saltin 1973). The muscles involved alter their power production, reducing the relative work load from 25.9% to 21.1% of maximal dynamic force (1RM). The power might be produced with lower relative force, thus further reducing the costs of executing the work. Motor units are believed to be recruited in a way such that slow twitch motor units are recruited first. The fast twitch fibres have to be recruited later to provide the necessary power output when the power or force requirements increase, which might be an additional explanation as to why the C_{dp} increased after the increased 1RM (Behm and Sale 1993).

There were no significant differences in C_{dp} during three different submaximal intensities (60%, 75% and 90% of $\dot{V}O_{2\max}$) on the ski ergometer. This was in line with the results of Helgerud and Wisloff (1998), who reported no significant differences in work efficiency at 60%–95% of $\dot{V}O_{2\max}$ in female marathon runners. The values in this study were in line with those of Helgerud and Wisløff (1998). However, Svedenhag (1995) suggested a decline in running C as the exercise intensity increased during different submaximal speeds, and like Helgerud (1993) he also emphasize that the unit used in the expression of running C should take the dimensional analyses into account. In the present study, C_{dp} was expressed as ml·kg$^{-0.67}$ body mass·m^{-1}. How exercise efficiency differs with increasing intensity is still not clear, particularly concerning the upper body, and the subject should be addressed in future research.

Body mass did not increase among the subjects, but an increase in muscle volume might still have occurred. Isometric peak force increased significantly, which was different from the findings by Kaneko et al. (1983). This may indicate a non-specific training response, due to velocity specificity or from mobilization. Behm (1995) observed that the increased strength in the early stage of high resistance-training was not associated with an increase in the muscle cross-sectional area. He thus suggested a possibility of increased frequency of nerve firing to the working muscle. An increased force-developing ability may occur as the motor units develop a lower recruitment threshold and an increased firing frequency. The maximal strength-training regimen in the present experiment was set up to put pressure on training effects from neural adaptations with little or no hypertrophy (Schmidtbleicher 1992; Sale 1992; Behm 1995).

Maximal strength-training in cross-country skiers, emphasizing neural adaptations, will probably not result in pronounced hypertrophy. It has been found that the muscle mass of the upper body is lower than the critical mass, the limitation during double-poling being both central and peripheral (Helgerud and Wisløff 1998). It is possible that an endurance-trained increased upper body muscle mass could decrease the peripheral limitations and increase $\dot{V}O_{2,\mathrm{peak}}$, and thereby increase the ability to compete effectively in cross-country skiing. During systematic strength-training over a period of time, some hypertrophy will probably occur in all muscle fibre types. Several studies have indicated that the fast-twitch fibres show the greatest amount of hypertrophy (Schmidtbleicher 1992; MacDougall 1992). Endurance-trained athletes such as cross-country skiers have a majority of slow-twitch muscle fibres. Shepard et al. (1988) concluded that exercise using both legs was limited by central factors, one-legged exercise was limited both by central and peripheral factors, and exercise with the arms was limited entirely by peripheral factors. However, they used arm cycling, which involves the use of less muscle mass than double-poling on the ski ergometer. This illustrates the possibility that there seems to be a critical muscle mass below which the limitation is mainly one of the peripheral factors involved. No studies using more than 9 weeks of maximal strength-training in endurance athletes have been reported, and the subject should be addressed in future research.

Performance development might differ between subjects using similar training regimens. In this experiment, each subject made notes of the training he had done after every training session. The training programme involved an increase in load of 30 N every time the subject was able to carry out three times six repetitions. This reduced the next session to very few repetitions, because of the 7%–10% increase in load. A more gradual increase in load might have given an even better 1RM enhancement.

The units used to express force and power are a main consideration in deciding how the results should be expressed. During the data analyses, both the peak force and the average force during the modified pull-down were recorded. If the results are expressed as average force the curves are not comparable with other reported results; for example, Kaneko et al. (1983) used the load unit as force on the x-axis. The biomechanically correct expression of power is the product of force and velocity (Knuttgen and Kraemer 1987). Force is the value that is applied to the weights, commonly expressed in newtons, not the absolute mass of the load, which is normally expressed in kilograms. In the present study, the force was expressed as load, which is the real mass lifted, in order to be able to compare with results from earlier studies. An expression of power on the basis of mass and average velocity might be acceptable.

The developments in training for cross-country skiing have put more emphasis on upper-body work than in the past. Using the classical diagonal technique, it has been suggested that each arm contraction represents only 10%–20% of the maximal dynamic force (Bergh 1982). The arm force in the skating technique has shown higher values than in the diagonal technique (Pierce et al. 1987). A human moving in an upright posture has adapted to using only a part of his total muscle mass for locomotion. The result of this is that his cardiovascular dimensions are scaled in such a way that they support only a fraction of the muscles in terms of their potential for perfusion during more intense exercise. According to the conductance theory, $\dot{V}O_{2,peak}$ could be limited mainly by peripheral factors such as the quantity of the muscle mass involved, capillary density, mean transit time and oxidative capacity (Shepard et al. 1988). But, as the mass of the active muscles increases, $\dot{V}O_{2,peak}$ could be limited by both central and peripheral factors, until a point is reached where only central factors represent the limitation of $\dot{V}O_{2max}$. The blood flow would be constricted mobilizing 15% of maximal dynamic force, and contractions of 70% of maximal voluntary force might cause a complete shut-down of the capillaries (Shepard et al. 1988), thus indicating a restriction of blood flow in double-poling. This restriction might be reduced by the increased maximal strength-training in this study, due to a subsequent relative reduction of force at similar loads.

The frequency of poling during double-poling on the ski ergometer did not change in either of the groups from the pre- to post-tests, in line with the results from Helgerud and Wisløff (1998) and Wisløff and Helgerud (1998). As the experiment group significantly increased the 1RM, the relative load for each repetition was reduced. The increased rate of force development and peak force of a standard work load gives a longer atonic period between the muscle contractions, which might improve the conditions for circulation and thereby increased *C*.

The $\dot{V}O_{2,peak}$ and $Th_{an,dp}$ in the upper body did not change during the experiment, as shown in earlier studies of maximal strength-training in endurance athletes (Hickson et al. 1988; Helgerud and Wisløff 1998; Wisløff and Helgerud 1998). Consequently, there should not be any negative effects on these parameters due to 9 weeks of maximal strength-training, although the absence of an increase in $\dot{V}O_{2,peak}$ and $Th_{an,dp}$ might indicate negative effects. The experiment group trained 14.0 (2.4) h a week, mostly engaging in endurance-training. Therefore, one would have expected an increased $\dot{V}O_{2,peak}$ and $Th_{an,dp}$ to be seen. However, the subjects in this study had been exposed to large amounts of training for many years, with only limited variations during the year. The high $\dot{V}O_{2,peak}$ values confirm this. Possibly there was not sufficient upper body endurance-training, due to the training conditions, to achieve an increased $\dot{V}O_{2,peak}$ and $Th_{an,dp}$.

The maximal strength-training exercise was selected according to movement specificity. Cross-country skiers should be familiar with the movements on the modified lat pull-down apparatus, and any strength gain due to a learning effect would be minimal. The particular strength-training and test exercise would, in the last part of the movement, activate a small muscle mass, in combination with a high biomechanical moment (Fig. 2). Thus, the criteria set in this study to get the modified pull-down movements accepted were designed to reduce the influence of the last part of the movements.

During the isometric test on the modified pull-down apparatus, the subjects arms started in the same position as at the start of the strength-training movement. The muscle groups involved were stretched to more than their resting position. Since the other results from the tests are based on identical initial force development, in the identical range of motion, this is considered to be the most valid position.

The significantly increased rate of force development, through the increased peak force and shorter time to peak force, in line with the results of Hoff et al. (1999), would give a shorter time for the restriction of blood flow. In turn, this would reduce the local limitations to the delivery of oxygen and substrates. Studies concerning the peripheral blood circulation should be set up, to evaluate the effects on the circulation of maximal strength-training. Future research could study the effects of maximal strength-training for more than 9 weeks, to evaluate development of hypertrophy and neural adaptations. Relationships with other fields such as those of rehabilitation and the prevention of muscle-skeletal injuries should also be examined.

Conclusion

Increased 1RM and thereby increased *C* in the upper body of male cross-country skiers may partly be a result of increased peak power and a shift in the power curve. The skiers are able to develop higher speed at the same load. The increases in power and rate of force development, rather than the increased 1RM per se, might be what alters endurance performance; alternatively, a reduced relative work load could increase *C*. In line with previous findings, the practical implications from the results of this study is that well-trained cross-country skiers could add maximal strength training to their training regimen.

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