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Maximal strength training improves aerobic endurance performance

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The aim of this experiment was to examine the effects of maximal strength training with emphasis on neural adaptations on strength- and endurance-performance for endurance trained athletes. Nineteen male cross-country skiers about 19.7 ± 4.0 years of age and a maximal oxygen uptake ($VO_{2\,max}$) of 69.4 ± 2.2 mL × kg^{-1} × min^{-1} were randomly assigned to a training group ($n = 9$) or a control group ($n = 10$). Strength training was performed, three times a week for 8 weeks, using a cable pulley simulating the movements in double poling in cross-country skiing, and consisted of three sets of six repetitions at a workload of 85% of one repetition maximum emphasizing maximal mobilization of force in the concentric movement. One repetition maximum improved significantly from 40.3 ± 4.5 to 44.3 ± 4.9 kg. Time to peak force (TPF) was reduced by 50 and 60% on two different submaximal workloads. Endurance performance measured as time to exhaustion (TTE) on a double poling ski ergometer at maximum aerobic velocity, improved from 6.49 to 10.18 min; 20.5% over the control group. Work economy changed significantly from 1.02 ± 0.14 to 0.74 ± 0.10 mL × kg$^{-0.67}$ × min^{-1}. Maximal strength training with emphasis on neural adaptations improves strength, particularly rate of force development, and improves aerobic endurance performance by improved work economy.

Abbreviations

1RM	= one repetition maximum
C_{dp}	= work economy when double poling at maximal aerobic velocity
CON	= control group
$f_{c\,max}$	= maximal heart frequency
HRT	= high resistance training group
PF	= peak force
PF_{60}	= peak force at 60% of 1RM
TPF	= time to peak force
TPF_{60}	= time to peak force at 60% of 1RM
TTE	= time to exhaustion
$VO_{2\,max}$	= maximal oxygen consumption
$VO_{2\,peak}$	= peak oxygen consumption
$[la^-]_b$	= blood plasma lactate concentration

The effect of combined strength and endurance training on physical performance has become a popular research topic in the last decade. It has been concluded that endurance training inhibits or interferes with strength development in several studies (Hennessy & Watson, 1994; Kraemer et al., 1995). Less research has been carried out to determine how strength training might influence endurance performance. Short-term endurance performance (4–8 min) in cycling and running has been shown to improve after 8–10 weeks of maximal strength training of the quadriceps muscles (Hickson, Rosenkoetter, Brown, 1980; Hickson, Dvorak, Gorostiaga, Kurowski, Foster, 1988). Hickson et al. (1988) concluded that increased strength in well-trained endurance athletes without increased body mass, is unlikely to have a negative effect on endurance performance. Nakao, Inoue, Murakami (1994) and Bishop, Jenkins, Macinnon, Mceniery, Carey (1999) did not find enhanced endurance capacity or performance even if maximal strength showed a substantial increase. Johnston, Quinn, Kertzer, Vroman (1997) also found a substantially improved maximal strength and links the finding to improved work economy, even though oxygen uptake on the submaximal workload where work economy was tested did not change. The work economy change is thus related to increased body mass from the strength training. Work economy will be overestimated when expressed as a 1:1 function of the body mass. Paavolainen, Häkkinen, Hämäläinen, Nummela, Rusko (1999) employed a wide spectrum of plyometrics and explosive strength training, did not change maximal strength, but showed enhanced power production and improved maximal oxygen consumption ($VO_{2\,max}$). However, an improvement in running economy and maximal velocity at an anaerobic treadmill running test were present. They concluded that the improved work economy was owing to the enhanced power production, but the use of several interventions simultaneously makes it difficult to trace physiological mechanisms behind the changes in dependent variables. Hoff, Helgerud, Wisløff (1999) employed a strength training regime that was supposed to alter maximal strength primarily by neural adaptations, and thus did not alter the body mass, and showed that increased maximal strength in a cross-country skiing double poling exercise enhanced double poling work economy in well trained female cross country skiers.

Training for improvement in one repetition maximum (1RM) with focus on neural adaptation, is associated with minimal hypertrophy (Sale, 1992; Hoff, Berdahl, Bråten, 2001), but substantial strength gains primarily from coordination (Almåsbakk & Hoff, 1996). Neural adaptation is a term used to describe several adaptations in the body. The term neural adaptation includes: alterations in recruitment, rate coding, synchronization of motor units, reflex potential, co-contractions of antagonists, and synergistic muscles (Behm, 1995). However, despite lack of hypertrophy, changes in contractile enzymes and hormonal changes cannot be excluded. To ensure optimal neural adaptations in a strength training program, it is important to stress all motor units, especially the high threshold motor units, to achieve maximal muscle activation (Behm, 1995). This maximal strength training increases the peak force (PF) which is the highest registered force developed during one repetition of a maximal voluntary contraction. An equally important factor connected to endurance performance might be the athletes' ability to develop force rapidly. While the external load is low, the influence of maximal strength diminishes and the rate of force development seems to be the predominant factor (Schmidtbleicher, 1992; Almåsbakk & Hoff, 1996). To improve the rate of force development, maximal strength training methods should be used (Schmidtbleicher, 1992; Hoff & Almåsbakk, 1995). The training is characterized by high mobilization of force, high loads, and few repetitions per set (Schmidtbleicher, 1992; Hoff et al., 1999). To further try to uncover mechanisms behind improved work economy, the aim of this experiment is to distinguish between the different effects of a maximal-strength training program that emphasizes maximal mobilization of force in the concentric part of the action. This is carried out by analyzing strength- and endurance-characteristics of well-trained male cross-country skiers, as measured on a cable pulley and a ski ergometer. Differences between male and female athletes are obviously not only genetic, but are also influenced by level of selection, training and competition. In this study male subjects are used which opens for some evaluation of gender differences. The hypotheses are that after the experimental period, 1RM will increase, time to PF (TPF) at a standardized submaximal strength load will decrease, and work economy at a standardized aerobic workload and endurance performance will improve. No change is expected in the body weight parameter.

Methods

Subjects

Nineteen male cross-country skiers volunteered to participate in this study. The experiment was carried out in the preseason period. The experiment consisted of 2 days of pretesting, an 8 week period of training, and 2 days of post-testing. The subjects were informed of the content and the time span of the experiment but were not informed of the hypothesis for the experiment. Each subject reviewed and signed consent forms approved by the Human Research Review Committee before participating in the study. A selection criterion was that the subjects were well-trained cross-country skiers with VO_{2max} higher than 65 mL kg^{-1} min^{-1}. The subjects were not adapted to neither the ski ergometer nor the cable pulley apparatus. The subjects were randomly assigned into one of the two groups. Nine subjects formed the high resistance training group (HRT), while 10 subjects made up the control group (CON).

Three more subjects were initially allowed started, but were excluded from the study later. In the HRT group, two subjects were excluded owing to a lack of high resistance training. The selection criterion was that the subjects should have undergone at least 65% of the training. One subject was excluded from the CON group, as he did not attend the post-test. The subjects' anthropometric and physiological characteristics are presented in Table 1.

Apparatus

Maximal strength training and testing was carried out using a modified cable pulley apparatus, designed to simulate the double poling movements in cross-country skiing (Eleiko Sport, Sweden), recently described (Hoff et al., 1999). The subjects

Table 1. Physical characteristics of the cross-country skiers before the experiment

	Age (year)	Body mass (kg)	Height (cm)	$VO_{2\,max}$ (L × min^{-1})	$VO_{2\,max}$ (mL × kg^{-1} × min^{-1})	$VO_{2\,max}$ (mL × kg$^{-0.67}$ × min^{-1})	$f_{c\,max}$ (beats × min^{-1})
HRT group	20.4	70.7	175.7	4.9	69.7	282.9	192
($n=9$)	(4.3)	(4.5)	(3.1)	(0.3)	(2.3)	(9.2)	(6.7)
CON group	19.2	75.6	183.0	5.2	69.1	287.0	193
($n=10$)	(3.9)	(5.4)	(4.1)	(0.4)	(2.3)	(12.9)	(5.7)

(SD) = standard deviation; $VO_{2\,max}$ = maximal oxygen uptake; $f_{c\,max}$ = maximal heart rate.

performed the pull-downs sitting on a bench mounted 2 m from the pulley apparatus. A locking mechanism over the thigh prevented undesired movements. The load could be adjusted in steps of 3 kg. Weight tolerance was ± 1% on the cable pulley. Force parameters were measured using a force transducer (Revere Transducers, California, USA) mounted between the pulley cable and the handle bar. The force transducer was connected to a computer via an A/D converter. The transducer responds linearly within a load range of 0–250 kg with a reproducibility of 0.1% (Instruction manual Revere Transducers, California, USA).

Prior to the test, the force transducer was calibrated using a dynamometer (Dynamometer no. 22, Dresden, Germany) with 0 and 40 kg. The dynamometer has an accuracy of 0.1% according to the manufacturers specification.

The $VO_{2\,max}$ was measured while running on a treadmill using a gas analyzing device (JAEGER EOS-sprint, Gmbh Wurtzburg, Germany) described by Versteeg & Kipperslius (1989) showing an accuracy of the oxygen consumption measurements of ± 3% of the measured value.

Short-range radio telemetry (Polar Sporttester, Polar Electro, Finland) was used to measure heart frequency (f_c). Blood plasma lactate concentration ($[la^-]_b$), unhemolyzed, analyzed immediately after fingerprick sample was drawn, was determined using a YSI Model 1500 Sport Lactate Analyzer (Yellow Springs Instrument Co., USA).

Ski double poling was simulated on a specially equipped ski ergometer recently described in detail by Wisløff & Helgerud (1998a,b).

In brief, the athlete stands on a freely wheeled platform and executes the classic double poling movement against a load determined by the combination of platform inclination and dynamometer velocity. As when running on a treadmill, the subjects' position on the ergometer is dependent on the matching of applied power to the ergometer velocity. The ski ergometer is equipped with force transducers for the acquisition of poling force vs. time data. Reliability and validity tests for the ski ergometer, presented by Wisløff & Helgerud (1998a), showed that there were no differences in power output (Watt) or oxygen uptake (VO_2) at the same exercise stages between the double poling skiing and the ski ergometer, and the coefficient of variation was 2.0 and 2.5%, respectively. There were no differences between peak oxygen consumption ($VO_{2\,peak}$) as measured when double poling on ski and on the ski ergometer in the validity testing (Wisløff & Helgerud, 1998a).

Testing

In each testing period, six tests were completed over 2 days. This consisted of three strength tests, one test running at the treadmill and two tests on the ski ergometer.

Day 1

Before strength test sessions, the subjects executed a standardized warm-up program. This program consisted of two parts, a general and a specific portion. The general portion consisted of 10 min running at approximately 50–60% of the VO_{2max}. The special portion included 2 series with 8 repetitions of about 50% of 1RM on the cable pulley apparatus.

After completing the standardized warm-up program, the subjects started the test with a load as near to the expected 1RM as possible. The load was increased by 3 kg after each successful lift. The description for a successful lift consisted of the following five points. First, before the test was started, the weight was lifted until it was hanging free. Second, the starting position mimicked the starting position of the double poling action. Third, the action of the lift was a smooth and continuous motion. Fourth, the lift was completed with an elbow angle of more than 90°. Fifth, a successful lift was registered when the subjects' hands touched a cardboard sheet placed 10 cm behind the hips. After three unsuccessful attempts at the same load, the last successfully completed load was registered as the subjects' 1RM. It should be noted that the 1RM test was carried out without the force transducers.

Following 10 min rest, the subjects performed a test with approximately 80% of 1RM. Two trials were performed and analyzed, and the best was used in the results. In addition, a single series of 24 repetitions at a standardized load of approximately 60% of initial 1RM was tested. The first two and the last two repetitions in the series were analyzed and the best were used in the results. On the test at 80 and 60% of 1RM, PF was measured and TPF was measured for the range from 10 to 90% of the PF. The PF and TPF were tested using the force transducer attached to the modified cable pulley apparatus.

Following the strength tests, VO_{2max} was determined by treadmill running at 6° inclination. The VO_{2max} protocol is described in detail by Åstrand & Rodahl (1986). Briefly, after a 20 min warm-up on the treadmill at approximately 50% of VO_{2max}, the treadmill speed was progressively increased every minute until VO_{2max} was reached. Additional markers which show that VO_{2max} has reached, was flattening of the oxygen curve, despite an increase in exercise intensity and respiratory exchange ratio above 1.05 and $[la^-]_b$ above 6 mmol L^{-1}. The highest f_c during the last minute was taken as maximal heart frequency ($f_{c\,max}$).

Day 2

The $VO_{2\,peak}$ in upper body work was determined according to the protocol described by Wisløff & Helgerud (1998a) using 4° inclination of the ski ergometer. Thereafter, a minimum of 30 min rest was allowed prior to the testing time to exhaustion (TTE). A 10 min warm-up with a work load estimated to 50% of $VO_{2\,peak}$ preceded the test. The test was started at a speed of 171 m min^{-1} and increased after 2 min to 181 m min^{-1}, and after two more minutes to 198 m min^{-1}. After the 6 min of work, the subjects were asked to continue until failure, operationalized as keeping in front of a marked position on the rails of the ergometer. The work economy in double poling at maximum aerobic velocity (C_{dp}) was calculated by using the average of the last two measurements (time 1.5 and 2 min) of VO_2 (mL × $kg^{-0.67}$ × min^{-1}) at the speed of 181 m min^{-1}, which also was the highest submaximal speed all subjects performed. The criteria used to secure a steady state VO_2 at that speed was a difference of less than 2.5% between the two measurements.

Training program

For the HRT group, approximately 45 min per week out of a training time of approximately 10 h $week^{-1}$ 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 between series was 3–4 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 the effect on performance owing to the investigators expression of concern only with the HRT group's training (Hawthorne effect), the training sessions were monitored only three times throughout the training period by the investigator, but every week by their trainers. The strength training performed by the CON group was limited to their traditional 'strength endurance' training, with an intensity of less than 85% of 1RM. Subjects recorded every training session throughout the eight week training period using a diary. The endurance training was divided into three intensity zones, 60–85%, 85–90% and 90–95% of maximal heart rate. Type of activity was also reported, e.g. skiing, roller skiing, running and so on. The strength training was also reported as number of reps, series, loads and time spent.

Statistics

Statistics were calculated using SPSS 6.0 for Windows. To calculate changes from pre to post-test between groups, Repeated Measures ANOVA was used. To determine changes within the group, a paired t-test was used. Results were accepted as significant at $P < 0.05$. The results are presented as means and standard deviations.

Results

The HRT group carried out 79 ± 16.4% of the planned strength training sessions. The HRT group trained 9.6 ± 1.6 h week^{-1}. The CON group trained 10.1 ± 2.3 h week^{-1}. The dominant training form was aerobic endurance training. In the first part of the training period, most of the endurance training performed was running. In the last part of the training period, most of the endurance training was skiing. No training volume differences between the groups were observed.

After the training period, the subjects within the HRT group showed a significant 9.9% improvement in 1RM, while the results for the CON group did not change significantly (Table 2). Furthermore, the HRT group as a whole showed significantly higher 1RM improvement compared to the CON group (Table 2).

The PF at 80% of 1RM (PF_{80}) improved significantly by 34% from pre-to post-test for the HRT group, but stayed unchanged for the CON group (Table 2). The PF at 60% of 1RM (PF_{60}) in the first and last repetitions in a series of 24 repetitions increased significantly by 33 and 34%, respectively, for the HRT group, and was, at the post-test, significantly higher compared to the CON group.

Changes in rate of force development are given by TPF. The HRT group showed a significant decrease in TPF from pre-to post-test. A 50% reduction for the loads of 80% of 1RM (TPF_{80}) were shown, while a 60% reduction was shown for the first and the last repetitions of the series of 24 pulls at 60% of 1RM (Table 2). Between the groups, however, statistically significant differences in TPF in the post-test were only shown in the last repetition of the PF_{60} series.

A significant increase of 56% in TTE during the 8 week training period was shown for the HRT group. Likewise, the CON group improved significantly in this parameter by 25%. The difference in improvement from pre to post-test is, however, significant when comparing the two groups (Table 3). The C_{dp} at the speed of 181 m min^{-1} changed significantly from pre to post-test in the HRT group (Table 3).

After the TTE test, $[la^-]_b$ did not change from pre to post-test for either group nor was there observed any change in body weight in either of the groups during the 8 week training period (Table 2). No significant differences were found in VO_{2max} or VO_{2peak} between the two groups in the pre test or in the post-test (Tables 3 and 4).

Discussion

The findings of this experiment build on the findings from Hoff et al. (1999) and demonstrate that maximal strength training with emphasis on maximal mobilization of force in the concentric action improve work economy on an aerobic workload and thus improve aerobic endurance performance. A small increase in maximal strength paralleled with a great increase in TPF indicates that the rate of force development seems to be more important than the improved strength as such, in line with the indications also made by Paavolainen et al. (1999) and might explain why other experiments fail to show a relation between muscle strength and endurance performance.

Table 2. Results from the strength tests

	Body mass (kg)	1 RM (kg)	Peak force			Time to peak force		
			PF_{80} (N)	PF_{60} (N)	PFL_{60} (N)	TPF_{80} (ms)	TPF_{60} (ms)	$TPFL_{60}$ (ms)
Pretest								
HRT group	70.7	40.3	455	365	347	180	200	200
(n = 9)	(4.5)	(4.5)	(93.7)	(60.4)	(61.7)	(50)	(40)	(80)
CON group	75.6	40.5	490	388	390	160	190	150
(n = 10)	(5.4)	(4.5)	(80.9)	(58.5)	(59.1)	(60)	(70)	(50)
Post-test								
HRT group	71.3	44.3	611	488	471	90	80	80
(n = 9)	(5.2)	(4.9)*a	(95.6)*a	(83.6)*a	(83.6)*a	(20)a	(20)a	(20)*a
CON group	76.1	41.1	556	444	428	130	110	120
(n = 10)	(5.6)	(5.1)	(90.2)	(70.7)a	(53.7)	(40)	(40)a	(30)

(SD) = standard deviations; 1RM = one repetition maximum at the strength apparatus; PF = peak force; PFL = peak force, last repetition of a series of 24 repetitions; TPF = time to PF; TPFL = time to PF, last repetition of a series of 24 repetitions; * = significant differences between groups, $P < 0.05$; a = significant differences within groups, $P < 0.05$. N = newton; ms = milliseconds.

Table 3. Results from tests on the ski ergometer

	$VO_{2\,peak}$ (L × min^{-1})	$VO_{2\,peak}$ (mL × kg^{-1} × min^{-1})	$VO_{2\,peak}$ (mL × kg$^{-0.67}$ × min^{-1})	TTE (min)	C_{dp181} (mL × kg$^{-0.67}$ × m^{-1})	$[la^-]_b$ TTE (mmol × L^{-1})
Pretest						
HRT group (n=9)	4.1 (0.4)	58.7 (3.9)	239 (17.1)	6.49 (1.6)	1.02 (0.14)	7.21 (1.0)
CON group (n=10)	4.6 (0.4)	60.2 (3.8)	251 (16.5)	7.45 (1.1)	0.97 (0.05)	8.15 (0.7)
Post-test						
HRT group (n=9)	4.3 (0.4)	60.3 (2.5)	246 (11.4)	10.18 (1.7)*a	0.74 (0.10)*	6.73 (0.9)
CON group (n=10)	4.7 (0.4)	61.1 (3.1)	256 (13.5)	9.31 (1.3)a	0.83 (0.13)	7.49 (1.3)

(SD) = standard deviations; $VO_{2\,peak}$ = peak oxygen uptake during work on the ski ergometer; TTE = time to exhaustion during work on the ski ergometer; C_{dp181} = cost of poling; $[la^-]_b$ TTE = blood plasma lactate concentration after the time to exhaustion test; * = significant differences between groups, $P < 0.05$; a = significant differences within groups, $P < 0.05$.

Table 4. Results from treadmill test (6° inclination)

	$VO_{2\,peak}$ (L × min^{-1})	$VO_{2\,peak}$ (mL × kg^{-1} × min^{-1})	$VO_{2\,peak}$ (mL × kg$^{-0.67}$ × min^{-1})
Pretest			
HRT group (n=9)	4.9 (0.3)	69.7 (2.3)	283 (9.2)
CON group (n=10)	5.2 (0.4)	69.1 (2.3)	287 (12.9)
Post-test			
HRT group (n=9)	5.0 (0.3)	69.6 (1.9)	284 (7.6)
CON group (n=10)	5.4 (0.5)	70.8 (2.8)	295 (13.3)

(SD) = standard deviations; $VO_{2\,max}$ = maximal oxygen uptake.

The developments in cross-country skiing have put a greater emphasis on upper body work than before. Using classical diagonal technique, it is suggested that each arm contraction only represents 10–20% of the maximal force (Bergh, 1982). The arm force in skating technique has shown higher values than the diagonal technique (Pierce, Pope, Renstrøm, Johanson, Dufek, Dillman, 1987; Smith, 1989), and with changes in speed and steep uphill slopes contractions closer to maximal would be expected.

The blood flow is constricted at contractions mobilizing 15% of maximal force, and contractions of 70% of maximal voluntary force might cause a complete lock of the capillaries (Shephard, 1992), thus indicating a constriction of blood flow during the concentric phase of the dynamic movement of double poling. The possibility that this constriction is reduced by the increased maximal strength owing to a consecutive relative reduction of force at similar loads is indicated only from this experiment, and it should be addressed in future experiments.

Little research is carried out enlightening the effects of strength training on endurance performance. If a higher level of strength can be achieved without an increase in body mass, Hickson et al. (1988) states that there should be no reason why endurance performance should decrease. In the current study, a positive effect was found for endurance performance after 8 weeks of maximum strength training. The results show that both the HRT group and the CON group enhanced their endurance performance, expressed as TTE on the ski ergometer, after 8 weeks of training. The TTE was significantly longer for the HRT group than for the CON group after the training period.

The improvements in TTE were expected, but an enhancement of 56 and 25% for the HRT group and the CON group, respectively, was higher than expected from previous experiments (Johnston et al., 1997; Paavolainen et al., 1999). The difference of 31% between the HRT group and the CON group is the effect of the maximum strength training, while the first 25% is owing to other factors. Because the experiment was carried out during the preparation period for a new competitive season, an increase in endurance performance on the ski ergometer was expected owing to changes from general to more specific training. This change included more roller skiing, and skiing that involved the upper body to a greater extent.

An endurance performance consists of the elements VO_{2max}, anaerobic threshold and work economy (Saltin, 1973; Pate & Kriska, 1984). In this experiment, the work economy improved for the HRT group at 181 m min^{-1}. This could explain the differences in TTE between the groups. Neither VO_{2max}, nor VO_{2peak} in the upper body changed during the experimental period for either of the groups. This was not expected from the experimental introduction of training, but might have been expected from the alterations in the training situation close to the competitive season. Lack of change might be explained by the limited time span of this experiment, or may bring into question the effect of the training regimen used by the cross-country skiers. Lactate threshold was not measured in this experiment, however, it did not change in a similar experiment (Hoff et al., 1999). Lactate threshold is normally considered relatively stable when expressed as a percentage of $VO_{2\,max}$ or $VO_{2\,peak}$ (Hoff et al., 1999; Helgerud, Engen, Wisløff, Hoff, 2001). An explanation for increased work economy might be that improved 1RM or rather improved rate of force development and PF makes a standard submaximal load relatively smaller. The PF during the double poling at maximal aerobic velocity, relative to the highest PF measured, is reduced by 10%. Relative load determines the number of repetitions carried out to exhaustion in strength exercises, and thus determines energy cost per repetition. Helgerud (1994) has shown that running economy is similar at different velocities, which might be an argument against such a connection for aerobic workloads. This should be addressed in future research.

After eight weeks of maximal strength training, the HRT group showed an increase of 9.9% in maximum strength, expressed as 1RM, which was smaller than expected. Hoff & Almåsbakk (1995) showed a 32% increase in upper body strength in female handball players using a similar training regimen. Other experiments (Hickson et al., 1980; Hunter, Demment, Miller, 1987) have shown an increase in 1RM of about 30% after 8–10 weeks of maximal strength training of the legs.

The HRT group carried out 79% of the planned training, which might be part of the explanation for why the progress was lower than expected. A second explanation might be that the subjects did have a systematic training history of 5–6 years, including general strength training, which might reduce trainability given the relatively low training volume of the experiment. A third element might be that the muscle mass involved in the movement is relatively small, which might give a lower potential for maximum strength gains. A fourth explanation might be the muscle fiber distribution for the subjects in this group. Muscle fiber biopsies were not included in this experiment, but Bergh, Thorstensson, Sjødin, Hulten, Piehl, Karlsson (1978) showed that type I fibers are dominant, up to 75% of muscle fibers, for cross-country skiers. The high $VO_{2\,peak}$ values in the upper body among cross-country skiers might also be an indication for this (Mygind, Larsson, Klausen, 1991; Bilodeau, Roy, Boulay, 1995). This indicates that the subjects in this experiment might have less potential for maximal strength development than subjects from other sports, or randomly chosen subjects (Gollnick, Armstrong, Saubert, Piehl, Saltin, 1972).

In the current study, no measurements were carried out to directly evaluate whether the maximal strength improvement was owing to hypertrophy or neural adaptations. The maximal strength training regimen, however, was set up, to put pressure on training effects from neural adaptations with little or no hypertrophy (Sale, 1992; Behm, 1995). An increase in muscle volume might still have occurred even if body weight did not increase among the subjects. Other intramuscular responses such as changed calcium transport or changes in enzyme activity or hormonal responses might take place without hypertrophy. This is a line of further research.

In the current experiment, the subjects made notes after every training session. The training program involved an increase in load by 3 kg every time the subject was able to carry out three sets of six repetitions. This reduced the next session to very few repetitions, because of the 7–10% increase in load. A more gradual increase in training load might have improved 1RM enhancement.

The results in this study show that a relative small change in 1RM has a substantial effect upon endurance performance expressed as TTE on the ski ergometer for competitive athletes. The results are in line with the results from Hickson et al. (1988) in that strength improves TTE. The training for an enhanced 1RM leads to significant changes in PF and TPF at the respective loads. The TPF is more than halved in the post-test compared to the pretest for the HRT group at the PF_{60} test. A reduction at the last repetition of a continuous series of 24 repetitions shows that this training regimen is also improving TPF when performing repetitive double poling at the pulley with high loads. From these results, there might be a question of whether it is the rate of force development or power production improvements rather than the increased 1RM per set that alters the endurance performance. This might also have an effect on TPF when skiing, but was not tested in the present experiment. Further experiments should include TPF when skiing. These findings seem to be in line with the indications from Paavolainen et al. (1999) and the results from Hoff et al. (1999), that the increase in rate of force development might be a more important factor for improved work economy, and thus the endurance performance rather than the improved strength as such. That might also explain why other experiments fail to find improvements in endurance performance from strength training (Nakao et al., 1994; Bishop et al., 1999), which might lead to the conclusion that endurance and strength training modes are incompatible (Dudley & Djamil, 1985).

The current results suggest that cross-country skiers improved PF and TPF, while little change occurred in one repetition maximum of the trained muscles, after the strength training regime with emphasis on maximal mobilization of force in the concentric action. This highlights the importance of other strength parameters rather than maximal strength alone. Further, the results showed an improved endurance performance for male cross-country skiers, as expressed as TTE on a standardized aerobic work load on a ski ergometer. The improved performance was shown by the significantly longer TTE for the high resistance group than for the CON group after the training period, in line with the findings from Hoff et al. (1999) and in line with the indications made by Paavolainen et al. (1999).

Compared to the findings for female cross-country skiers in the experiment by Hoff et al. (1999) the improvements in work economy in this experiment is somewhat smaller, 80% vs. 20.8%, over the respective CON groups. Even if both the female and the male groups of cross country skiers are competitive skiers, the male skiers in this experiment are relatively better trained, as shown by their $VO_{2\,max}$ values. As males are stronger in upper body relative to females, comparative to leg strength, probably also contributes to higher response among females, as shown by a somewhat lower training response by males in all strength parameters.

The results from both the experiments show that the strength training with emphasis of maximal mobilization of force improves work economy and endurance performance correlated primarily to enhanced rate of force development, but also to changes in PF and 1RM. The contribution of other factors needs to be further investigated.

Perspectives

Strength training with emphasis on maximal mobilization of force should, based on the results in this experiment, be included in training for improved endurance performance for athletes as well as for rehabilitation and in preventive medicine. The effect is not likely limited to upper body work. In situations, where endurance is limited by heart or lung capacity, as for congestive heart failure or chronic obstructive lung disease, a similar leg training regime might offer improvements in endurance performance through a reduced oxygen cost and thus, quality of life improvements.

Key words: elite athletes; cross-country skiing; double poling; male; neural adaptations; work economy.

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