

Maximal strength training improves work economy in trained female cross-country skiers

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ABSTRACT

HOFF, J., J. HELGERUD, and U. WISLØFF. Maximal strength training improves work economy in trained female cross-country skiers. *Med. Sci. Sports Exerc.*, Vol. 31, No. 6, pp. 870–877, 1999. **Purpose:** The present study examines the hypothesis that maximal strength training improves work economy and anaerobic threshold in trained female cross-country skiers while working on a ski ergometer. **Methods:** Fifteen female cross-country skiers (17.9 ± 0.3 yr, 166.7 ± 1.3 cm, 60.1 ± 1.9 kg, and 55.3 ± 1.3 mL·kg⁻¹·min⁻¹) participated in the study. Eight skiers made up the high-intensity strength-trained group, and seven served as the control group. Endurance performance was tested on a specially instrumented ski ergometer. Strength training and testing simulated double poling in cross-country skiing. **Results:** A significant ($P < 0.001$) improvement in double-poling economy on the ski ergometer was observed among the strength-trained group. Anaerobic threshold did not change during the experimental period for either group. After a 9-wk training period, time to exhaustion increased from $5.2 (\pm 0.9)$ to $12.3 (\pm 1.6)$ min ($P < 0.001$) and from $4.0 (\pm 0.9)$ to $6.3 (\pm 0.9)$ min ($P < 0.01$) for the strength and control group, respectively. Time to exhaustion was significantly higher ($P < 0.001$) for the strength group compared with the control group after training. One repetition maximum increased 14.5% (1.8) ($P < 0.001$) in the strength group but was unchanged in the control group. Expressed in relation to peak force at one repetition maximum, strength training resulted in a significant reduction in the relative available force employed working on the ski ergometer ($P < 0.01$). Time to peak force at maximal aerobic velocity on the ski ergometer was significantly reduced in the strength-training group ($P < 0.01$). **Conclusions:** It is concluded that maximal strength training in the upper-body improved the double-poling performance by improved work economy. Work economy was improved by a reduction in relative workload and time to peak force while double poling. **Key Words:** MAXIMAL STRENGTH TRAINING, CROSS-COUNTRY SKIING, ENDURANCE PERFORMANCE, $\dot{V}O_{2\text{PEAK}}$, WORK ECONOMY, WOMEN

The effect of combined strength and endurance training on physical performance has been a popular research topic in the last decade. That endurance training inhibits or interferes with strength development is concluded in several studies (4,8,12,13,16). Few studies examine the impact of strength training on endurance performance. Hickson et al. (14) reported a 27% increase in one repetition maximum (1RM) after 10 wk with maximal strength training of quadriceps. Maximal oxygen uptake ($\dot{V}O_{2\text{max}}$) was unchanged during the same period whereas short-term endurance (4–8 min), measured as time to exhaustion during treadmill running and on a bicycle ergometer, increased by 13% and 11%, respectively. $\dot{V}O_{2\text{max}}$ and

peak oxygen uptake ($\dot{V}O_{2\text{peak}}$) achieved during sports specific activity are traditional determining factors of endurance performance (23,30,31). Other important factors such as anaerobic threshold and work economy should be included. Among individuals with similar $\dot{V}O_{2\text{max}}$ and/or $\dot{V}O_{2\text{peak}}$, work economy and performance can vary considerably (6,11,22).

A variable that complicates evaluation of the impact of strength training on endurance performance is the training status of the subjects investigated. The majority of studies investigating strength and endurance training interactions have examined sedentary or moderately active subjects, using a strength-training regimen with low resistance and a high number of repetitions. When subjects are initially untrained, this type of strength training can have a substantial effect on endurance performance and may operate via mechanisms that are similar to those observed in endurance training (17,24). However, in well-trained, specifically adapted athletes, auxiliary training methods may fail to

0195-9131/99/3106-0870/0

MEDICINE & SCIENCE IN SPORTS & EXERCISE

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Submitted for publication July 1997.

Accepted for publication January 1998.

TABLE 1. Physical and physiological characteristics of the cross-country skiers before the experiment.

	Age (yr)	Height (cm)	Mass (kg)	[Hb] (g·dL ⁻¹)	Hct (%)	VC (L)	FEV ₁ /VC (%)	VO _{2max}			f _{max}
								(L·min ⁻¹)	(mL·kg ⁻¹ ·min ⁻¹)	(mL·kg ^{-0.75} ·min ⁻¹)	(beats·min ⁻¹)
Strength (N = 8)	17.8 ± 0.4	164.9 ± 1.9	56.8 ± 2.3	13.6 ± 0.4	42.8 ± 0.7	3.7 ± 0.2	86.2 ± 2.4	3.1 ± 0.1	55.3 ± 2.2	208.5 ± 7.7	205 ± 1.9
Control (N = 7)	18.0 ± 0.4	168.7 ± 1.4	63.9 ± 2.6	14.3 ± 1.3	45.8 ± 0.7	4.2 ± 0.2	86.2 ± 2.8	3.5 ± 0.4	55.3 ± 1.6	217.4 ± 5.6	199 ± 1.8
Total (N = 15)	17.9 ± 0.3	166.7 ± 1.3	60.1 ± 1.9	13.9 ± 1.2	44.2 ± 0.6	3.9 ± 0.1	86.2 ± 1.7	3.3 ± 0.1	55.3 ± 1.3	212.6 ± 4.9	202 ± 1.5

X (SEM); [Hb], hemoglobin concentration in blood; Hct, hematocrit; VC, vital capacity; FEV₁, forced expiratory volume in 1 second; VO_{2max}, maximal oxygen uptake; f_{max}, maximal heart rate.

improve endurance performance (3,7) or even inhibit performance if they are performed at the expense of specific training volume. Trained athletes may have a narrower range for further beneficial skeletal muscle adaptations. They may also require greater task specificity to achieve continued improvement (9,20) even though a previous study (15) showed substantial strength improvement in a non-task-specific exercise in trained athletes with a carry-over effect to performance. In the present study, maximal strength training based on neural adaptations with maximum intended velocity of contraction in the concentric action was emphasized. Thus, increased body weight from hypertrophy should play a minor role (20,21). This type of training has been shown to improve rate of force development (21). Neural adaptation to strength training involves factors such as increased firing rate in motor neurons, better recruitment of motor units, and reduced co-contraction of antagonist muscles and is handled in detail elsewhere (21). As for endurance performance, one should have a nuanced view upon the strength capacity of cross-country skiers. One should take into consideration factors as peak force, time to peak force, the percentage of use of 1RM, and peak force at 1RM when cross-country skiing, in addition to the specific 1RM. Reducing the relative workload and reduced time to peak force could lead to better perfusion of working muscle and, thereby, improved efficiency (27).

Recently the impact of specific, high-intensity strength training on the upper-body skiing endurance of well-trained male cross-country skiers was examined (11). In that study, 1RM increased by 11% by using a cable pulley, and the time to exhaustion increased from 7.10 to 10.45 min while working on an upper body ski ergometer. The improvement in time to exhaustion was 25% higher in the training group compared with the control group. This was partly explained by a significant reduction in energy spent per unit distance, defined as double-poling economy. An additional explanation could be improved anaerobic threshold, however, which was not measured (11).

Cross-country skiing is unique in that all four limbs contribute to forward propulsion but to varying degrees, depending on the specific technique employed. During steep climbing employing the asynchronous skating technique, paddling, the upper body musculature may assume 50% of the force production load (28,29). During classic double poling on flat terrain, the upper body musculature assumes the full burden of propulsion. When these techniques are employed, higher maximal strength may reduce relative force generation required by the upper body, resulting in reduced intramuscular pressure and enhanced blood perfusion of the working muscles.

The aim of the present study was to examine the following hypothesis: 1) maximal strength training will improve the double-poling performance by improved work economy and anaerobic threshold, and 2) work economy improves by a reduction in relative workload (%1RM) and time to peak force while double poling at maximal aerobic velocity.

METHODS

Subjects. Fifteen female cross-country skiers, competing at the regional level in Norway, participated in this study after reviewing and signing consent forms approved by the Human Research Review Committee. Subjects were randomly placed in one of two groups: eight skiers made up the high-intensity, strength-trained group, and the remaining seven served as a control group. None of the subjects were familiar with the strength-training regimen and apparatus before the training period. For strength measurements, the data collectors were totally blind to the hypothesis being tested, and the data collectors for the endurance measurements were restricted from knowing the subjects' group location. The experimental design consisted of 3 d of preliminary physiological testing, a 9-wk training period, and 3 d of posttesting. The experimental period was carried out in the basic preparation phase of training (October–December). The subjects' anthropometric and physiological characteristics are presented in Table 1.

Training program. Each subject kept a record of all training during the experiment in a personal training diary. Except for the inclusion of the high-intensity strength program, the two groups did not differ substantially in their training. The average weekly training volume was similar at 8.5 ± 0.8 and 9.2 ± 1.2 h for strength group and control group, respectively. The composition of the total training volume for the two groups is presented in Table 2. Over the course of the 9-wk training period, the dominant mode of endurance training for all the subjects transitioned from running in the first 4 wk to roller skiing and skiing over the

TABLE 2. Time spent performing different activities expressed in percentages.

	Strength Group	Control Group
Endurance total		
Long distance	59 ± 2.7	62 ± 2.7
Interval	11 ± 2.7	10 ± 2.7
Strength total		
General	2 ± 6.2	13 ± 1.0
Maximal	7 ± 6.2	—
Other training	21 ± 4.9	15 ± 4.8

The percentages are calculated from total training time for each group. Other training involve activities such as stretching, soccer, and technique training. The exercise intensity of interval and long-distance training were performed with an exercise intensity of 85–95% and between 70–85% of f_{max}, respectively.

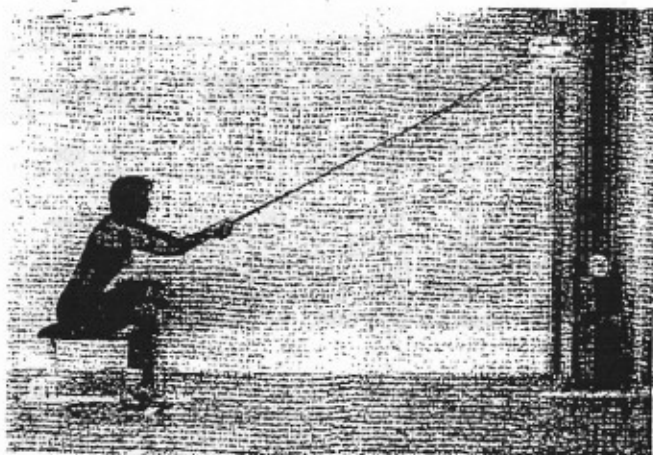


Figure 1—Strength-training apparatus.

last 5 wk. Nine weeks of maximal strength training has been shown to have effect upon both strength and endurance capacity (11,15,20,21) and was therefore chosen. The strength-training sessions performed by the strength group were observed every second week by the investigators and every week by their trainers. The training of the control group was observed by their trainers and via their training diaries.

The strength group performed a strength-training program for the upper body 3 d·wk⁻¹ throughout the experimental period, as designed by the investigators. The maximal strength-training program consisted of one exercise. Each session consisted of three sets of six repetitions with a load approximating the 6RM. Preliminary tests showed this load to be about 85% of 1RM. When a subject successfully executed three sets of six repetitions, the load was increased by 1 kg the next session. The strength training performed by the control group was limited to general strength training at intensities below 60% of 1RM or more than 20 repetitions.

Training and testing apparatus. Maximal strength training and testing were performed on the same apparatus, designed to simulate the movement pattern of the arms in classic double poling. The test apparatus was a modified cable pulley (Fig. 1). Subjects performed the pull-down sitting on a bench (Eleiko Sport, Halmstad, Sweden) placed 2 m from the apparatus. A locking mechanism placed over the thigh secured the subjects to the bench. The workload could be adjusted in 0.25-kg increments. A double-pole repetition was accepted when the subject's hands touched a pad mounted 10 cm behind the hip and when the elbow joint angle exceeded 90° at completion. Force parameters were measured using a force transducer (Revere Transducers, Breda, Holland) mounted at the junction of the weight stack and the pulley cable. The force transducer was connected via an A/D converter to a computer. The transducer responds linearly within a load range of 0–250 kg with a reproducibility of 0.1% (Instruction manual Scan-Sense, Toensberg, Norway). Before tests, the force transducer was calibrated using a dynamometer (Dynamometer no. 22, Dresden, Germany) with 0, 15, 30, and 40 kg. The dynamometer has an accuracy of $\pm 0.1\%$ according to the manufacturer's specifications.

Ski double poling was simulated on a specially instrumented ski ergometer (Fig. 2) recently described in detail elsewhere (30,31). Briefly, the athlete stands on a freely moving wheeled platform and executes the classic double-poling movement against a load determined by the combination of platform incline and dynamometer velocity. As when running on a treadmill, the athlete's position on the ergometer depends on the matching of applied power to the ergometer velocity. The ski ergometer is also equipped with force transducers for the acquisition of poling force-time data.

Heart frequency (f_c) was measured by short-range radio telemetry (Polar Sporttester, Polar Electro, Kempele, Finland). Oxygen uptake ($\dot{V}O_2$), maximal minute ventilation (V_E), respiratory exchange ratio (R), and breathing frequency were measured during each exercise stage using an Ergo Oxyscreen (Jaeger EOS sprint, Hoechberg, Germany). Unhemolyzed $[La^-]_b$ was determined with a YSI Model 1500 Sport Lactate Analyzer (Yellow Springs Instrument Co., Yellow Springs, OH).

Testing. Preliminary and post training tests were conducted over a 3-d period with 1 d of rest between each testing day. The order of testing and protocols for the pre- and post-tests were identical.

Day 1. Upon entering the laboratory, subjects had their hemoglobin (Hb), hematocrit (Hct), and lung function measured for normative data comparisons. For Hb and Hct determination, blood was drawn from a fingertip and analyzed immediately using the Refletron (Boehringer Mannheim, Mannheim, Germany) and Ames microspin (Bayer Diagnostic, Munich, Germany) devices, respectively. Vital capacity (VC) and forced expiratory volume in one second (FEV_1) were determined using a flow screen (Jaeger). After preliminary normative data collection (Table 1), subjects completed a 15-min general warm-up by treadmill running at approximately 50–60% of $\dot{V}O_{2max}$. Each subject then performed a specific warm-up, performing 20 repetitions of the pull-down exercise at approximately 50% of 1RM. After the warm-up and a brief rest, the pull-down load was increased with each successive repetition until the 1RM was

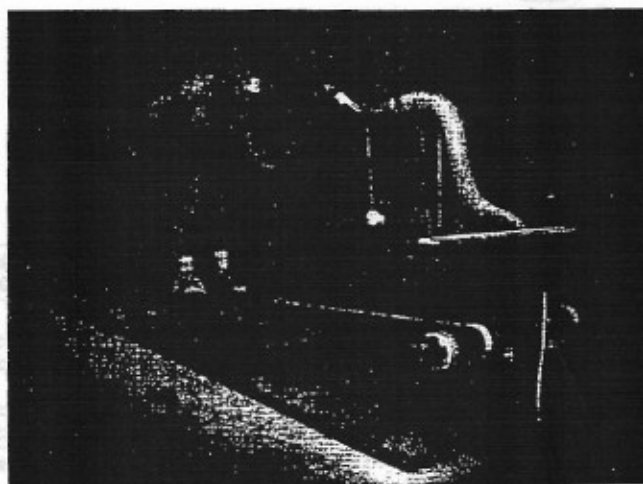


Figure 2—Double-poling ski ergometer.

TABLE 3: Anaerobic thresholds and double-poling economy.

	Th _{an}			Th _{an,ski}			Th _{an,power}	Th _{an,ski,power}	C _{ski}
	(L·min ⁻¹)	(mL·kg ⁻¹ ·min ⁻¹)	(mL·kg ^{-0.67} ·min ⁻¹)	(L·min ⁻¹)	(mL·kg ⁻¹ ·min ⁻¹)	(mL·kg ^{-0.67} ·min ⁻¹)	(Watt)	(Watt)	(mL·kg ^{-0.67} ·min ⁻¹)
Pre									
Strength group	2.7 ± 0.1 ^a	48.3 ± 1.6 ^a	183.0 ± 5.8 ^a	2.1 ± 0.9	38.1 ± 1.7	143.9 ± 5.8	139.8 ± 7.1 ^b	100.0 ± 6.1	1.42 ± 0.08
Control group	3.0 ± 0.1 ^a	47.8 ± 1.3 ^a	187.4 ± 4.1 ^a	2.4 ± 0.7	39.0 ± 1.5	153.0 ± 4.6	151.3 ± 5.1 ^b	102.9 ± 6.2	1.37 ± 0.11
Post									
Strength group	2.8 ± 0.2 ^a	47.5 ± 2.1 ^a	177.4 ± 8.1 ^a	2.5 ± 0.8	42.1 ± 1.4	161.9 ± 4.5	145.6 ± 9.7 ^b	107.2 ± 16.9	1.10 ± 0.07 ^a
Control group	3.1 ± 0.1 ^a	48.0 ± 1.3 ^a	189.7 ± 4.3 ^a	2.7 ± 0.1	42.0 ± 1.7	165.6 ± 5.4	157.9 ± 6.4 ^b	97.3 ± 19.0	1.47 ± 0.08

X (SEM); Th_{an}, anaerobic threshold while running on the treadmill; Th_{an,ski}, anaerobic threshold during work on the ski ergometer; Th_{an,power}, power output at anaerobic threshold while running on the treadmill; Th_{an,ski,power}, power output at anaerobic threshold working on the ski ergometer; C_{ski}, cost of poling working on the ski ergometer at test to exhaustion. Significant differences: * $P < 0.001$; ^a Significant higher than Th_{an,ski} ($P < 0.05$); ^b Significant higher than Th_{an,ski,power} ($P < 0.05$).

reached. Between each trial there was a 5-min resting period. After an accepted lift, the workload was increased by 0.25 kg to 3.0 kg according to the subject's request. After two consecutive nonaccepted attempts, the highest accepted attempt was registered as the 1RM. After a 15-min rest, the subjects performed 1 repetition of 80% of 1RM and a 20-repetition test at 60% of 1RM for the measurement of time to peak force (TPF). In the latter test, TPF was determined for the first and last repetition in the sequence. Subjects were informed to perform each repetition at maximum velocity.

After the strength tests, 1.5-h resting periods were given before anaerobic threshold (Th_{an}) and maximal oxygen uptake ($\dot{V}O_{2max}$) were determined during treadmill running (6°). The protocol used for measuring Th_{an} and $\dot{V}O_{2max}$ has been described previously (10). Briefly, Th_{an} determination began with a 10-min warm-up at 50–60% of $\dot{V}O_{2max}$, followed by measurement of baseline blood lactate concentration ([La]_b). Based on previous work in the author's laboratory (10), the Th_{an} was taken as the power output, $\dot{V}O_2$, or heart rate (f_c) that gave a $\Delta[La]_b$ of 1.5 mmol·L⁻¹ above baseline using 5-min work bouts during a continuous, graded protocol. Subjects performed 5-min exercise stages progressing in intensity between 60 and 95% of $\dot{V}O_{2max}$. Running speed was increased by 1 km·t⁻¹ at each stage, after a 20-s pause for blood sampling from a finger tip. After subjects reached Th_{an}, treadmill speed was increased to a level that brought the subject to $\dot{V}O_{2max}$, using traditional criteria (1), and close to exhaustion after about 3 min. The highest f_c during the last minute was taken as maximal heart frequency (f_{cmax}).

Day 2. On the second day of testing, the anaerobic threshold (Th_{an,ski}) and the peak $\dot{V}O_2$ achieved during the upper-body dominant activity of double-poling ($\dot{V}O_{2peak}$) was measured. After familiarizing subjects with the ski ergometer, the power output for warm-up was estimated.

The protocol for measuring Th_{an,ski} has been recently described (31) and is similar to that described above for treadmill running with two exceptions: the exercise stages were 3 min in duration, and the $\Delta[La]_b$ corresponding to Th_{an,ski} was 1.8 mmol·L⁻¹ above baseline. Subjects performed 3-min exercise stages progressing in intensity between 60 and 95% of $\dot{V}O_{2peak}$. Power output was increased by 20 W at each stage after a 20-s pause for measuring [La]_b. After the subjects reached Th_{an,ski}, the power output was increased to a level that brought the subject to $\dot{V}O_{2peak}$, using criteria previously described (30), and close to exhaustion after about 3 min. The highest f_c during the last minute was taken as peak f_c working on the ski ergometer (f_{cpeak}).

Day 3. The final day of testing consisted of an upper-body ski ergometer test to exhaustion.

Subjects performed a 15-min warm-up on the ski ergometer at an exercise intensity of about 60% of $\dot{V}O_{2peak}$, followed by a test to exhaustion. Double-poling exercise was performed to temporary exhaustion at the power output eliciting $\dot{V}O_{2peak}$ during day 2 testing (maximal aerobic velocity). This power output was identical in the pre- and post-tests. Exhaustion was considered the time-point when subjects could not maintain their position on the ergometer and the platform came behind a predetermined mark. Immediately after the test, a blood sample was taken from a finger tip for measurement of [La]_b.

During the exhaustive test on the ski ergometer, peak force (PF_{ski}) and time to peak force (TPF_{ski}) were measured from an average of 15 double-pole cycles collected 2 min after the start. The double-poling economy, or cost of poling (C_{ski}) during the test, was calculated by dividing the oxygen uptake (mL·kg^{-0.67}·min⁻¹) by the speed of poling (m·min⁻¹).

Statistical analysis. All results are reported as means (X) and standard error of mean (SEM) calculated by con-

TABLE 4. Percentage expression of physiological parameters.

	PF _{ski}	$\dot{V}O_{2peak}$	Th _{an}	Th _{an,ski}	Th _{an}	Th _{an,ski}
	(% PF 1RM)	(% $\dot{V}O_{2max}$)	(% $\dot{V}O_{2max}$)	(% $\dot{V}O_{2peak}$)	(% f_{cmax})	(% f_{cpeak})
Pre						
Strength group	43.7 ± 5.2	84.3 ± 1.2	88.1 ± 1.6	81.5 ± 2.6	93.1 ± 0.8	91.7 ± 1.3
Control group	47.1 ± 6.5	80.4 ± 4.2	86.4 ± 1.4	83.0 ± 2.1	93.2 ± 1.4	92.6 ± 0.6
Post						
Strength group	28.5 ± 2.3 ^a	88.9 ± 2.9	84.3 ± 1.7	87.4 ± 2.3	92.5 ± 1.0	93.2 ± 1.2
Control group	44.9 ± 3.6	84.7 ± 3.0	84.3 ± 2.0	84.9 ± 3.7	90.7 ± 1.0	91.3 ± 1.4

X (SEM); PF_{ski}, peak force during poling at the test to exhaustion; $\dot{V}O_{2peak}$, peak oxygen uptake at the ski ergometer; Th_{an}, anaerobic threshold running on the treadmill; Th_{an,ski}, anaerobic threshold at the ski ergometer.

Significant difference, $P < 0.01$.

TABLE 5. Results from tests on the ski ergometer.

	$\dot{V}O_{2peak}$ (L·min ⁻¹)	$\dot{V}O_{2peak}$ (mL·kg ⁻¹ ·min ⁻¹)	$\dot{V}O_{2peak}$ (mL·kg ^{-0.87} ·min ⁻¹)	TTE (min)	[La ⁻] _{TTE} (mmol·L ⁻¹)	Cycle rate - (ppm)
Pre						
Strength group	2.6 ± 0.1	46.5 ± 1.5	175.2 ± 5.8	5.2 ± 0.9	6.4 ± 0.4	68 ± 2.3
Control group	2.9 ± 0.1	46.7 ± 2.1	183.4 ± 7.4	4.0 ± 0.9	5.7 ± 0.2	64 ± 3.6
Post						
Strength group	2.9 ± 0.1	48.6 ± 2.2	189.3 ± 7.4	12.3 ± 1.6***	4.9 ± 0.2	64 ± 3.0
Control group	3.1 ± 0.2	50.8 ± 2.0	196.2 ± 10.4	6.3 ± 0.9*	5.6 ± 0.3	58 ± 4.3

X (SEM); $\dot{V}O_{2peak}$, peak oxygen uptake during work on the ski ergometer; TTE, time to exhaustion during work on the ski ergometer; [La⁻]_{TTE}, blood lactate concentration after the test to exhaustion; cycle rate, the frequency of poling per minute (ppm) during the test to exhaustion.

Significant differences: * $P < 0.01$; ** $P < 0.001$; * significant higher than the control group ($P < 0.01$).

ventional procedures. Repeat-measure ANOVA was used to determine differences in parameters between and within the strength and control group during the experiment. Correlations were calculated using Pearson product moment r . A P value ≤ 0.05 was considered statistically significant.

RESULTS

The strength group performed 88.0% ($\pm 4.4\%$) of the planned strength training. There were no initial differences in any physiological parameter between groups. The strength group had significantly improvement in double-poling economy (C_{ski}) (Table 3), and there was a significant correlation between the reduction in the relative force employed working on the ski ergometer and improvement in C_{ski} ($r = 0.67$, $P < 0.05$) and between TPF_{ski} and C_{ski} ($r = 0.86$, $P < 0.01$). There was also a correlation between the reduction in relative force employed ($r = 0.81$, $P < 0.01$), TPF_{ski} ($r = 0.77$, $P < 0.01$) C_{ski} ($r = 0.86$, $P < 0.001$), and time to exhaustion. There were no significant changes in Th_{an} and $Th_{an,ski}$ during the experiment (Tables 3 and 4).

After the 9-wk intervention period, time to exhaustion at maximal aerobic velocity on the upper body ski ergometer test increased 136.5% ($\pm 7.3\%$) ($P < 0.001$) and 57.5% ($\pm 5.7\%$) ($P < 0.01$) for the strength and control group, respectively. The improvement in time to exhaustion was significantly higher ($P < 0.001$) for the strength group compared with the control group after training (Table 5).

1RM increased 14.5% ($\pm 1.8\%$) ($P < 0.001$) in the strength group but was unchanged in the control group. The strength group increased the peak force at 1 RM by 36.1%, compared with no significant change in the control group (Table 6). The strength group had 27.0% ($\pm 5.9\%$) ($P < 0.03$) reduction in TPF_{ski} whereas the control group was unchanged after the experimental period (Table 6). PF_{ski}

expressed absolutely (N) did not change for any of the groups during the experiment (Table 6). After the training program, the strength group used significantly less force expressed in percentage of peak force at 1RM during double poling, compared with the results from the pretest (Table 4). No correlation was found for time to exhaustion and 1RM, but there was a significant correlation between improvement in 1RM and improvement in TPF_{ski} ($r = -0.78$, $P < 0.01$). The maximal strength training also resulted in higher power output at $\dot{V}O_{2peak}$ (Table 6). No differences were observed in poling frequency as a result of the training intervention (Table 5). The maximal strength training had no impact on body weight, and neither group changed body weight significantly over the course of the study. Body weight at the post tests were 56.5 (± 1.7) kg and 63.2 (± 2.4) kg for the strength and control group, respectively. Body weights from the pretests are presented in Table 1.

$\dot{V}O_{2max}$ and $\dot{V}O_{2peak}$ did not change significantly in either group during the experimental period (Tables 1 and 5). The values for $\dot{V}O_{2max}$ at the post tests were 3.3 L·min⁻¹ (± 0.1) and 3.7 L·min⁻¹ (± 0.3) for the strength and control group, respectively.

There was a correlation between $\dot{V}O_{2max}$ and $\dot{V}O_{2peak}$ ($r = 0.85$, $P < 0.001$), between $\dot{V}O_{2max}$ and Th_{an} ($r = 0.87$, $P < 0.001$), and between $\dot{V}O_{2peak}$ and $Th_{an,ski}$ ($r = 0.78$, $P < 0.001$), but no correlation between Th_{an} and $Th_{an,ski}$. $\dot{V}O_{2peak}$ and $Th_{an,ski}$ did not correlate with time to exhaustion. Th_{an} , for all subjects, corresponded to 84.0% of $\dot{V}O_{2max}$ or 91.0% of f_{cmax} whereas $Th_{an,ski}$ occurred at 86.3% of $\dot{V}O_{2peak}$ or 92.3% of f_{cpeak} .

No significant differences were found for minute ventilation, respiratory exchange ratio, f_c , and [La⁻]_{TTE} at $\dot{V}O_{2max}$ and $\dot{V}O_{2peak}$ during the experiment. The average values for the post tests are therefore presented (Table 7). There were no significant changes in Hb concentration or Hct during the experimental period. The values for Hb concentration were

TABLE 6. Results from the strength tests.

	1 RM (kg)	PF 1RM (N)	PF _{ski} (N)	Power output (Watt)	TPF80 (ms)	TPF60 ₂₀ (ms)	TPF _{ski} (ms)
Pre							
Strength group	24.8 ± 1.0	302 ± 3.6	132 ± 8.3	121.7 ± 6.3	370 ± 0.05	580 ± 0.04	370 ± 0.05
Control group	26.1 ± 2.1	314 ± 4.3	148 ± 15.4	135.7 ± 8.9	410 ± 0.03	590 ± 0.05	420 ± 0.05
Post							
Strength group	28.4 ± 1.2*	411 ± 3.8*	117 ± 16.3	152.9 ± 12.4*	260 ± 0.03*	450 ± 0.02*	270 ± 0.03**
Control group	26.3 ± 2.4	329 ± 2.8	148 ± 11.9	149.7 ± 16.7	400 ± 0.04	570 ± 0.04	430 ± 0.04

X (SEM) 1RM; one repetition maximum at the strength apparatus; PF 1RM; peak force at 1RM; TPF80; time to peak force at 80% of 1RM; TPF 60₂₀; time to peak force at 60% of 1RM at repetition number 20; PF_{ski}; peak force during work at the ski ergometer at the test to exhaustion; Power output; power output at $\dot{V}O_{2peak}$.

Significant differences: * $P < 0.05$; ** $P < 0.01$.

TABLE 7: Physiological parameters at $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$ during work on the ski ergometer (5° inclination) and during the treadmill test (6° inclination).

Variable	$\dot{V}O_{2peak}$	$\dot{V}O_{2max}$
Power output (Watt)	183.9 ± 14.5*	151.4 ± 9.7
\dot{V}_E (L·min ⁻¹)	110.4 ± 8.3	108.7 ± 5.3
f_c (beats·min ⁻¹)	202.0 ± 1.5	195.0 ± 1.4
R	1.13 ± 0.4	1.08 ± 0.5
[la ⁻] _b (mM)	6.7 ± 0.2	6.4 ± 0.7

X (SEM) ($N = 15$); data shown are average results ($N = 15$) from the post tests. \dot{V}_E , minute ventilation; R, respiratory exchange ratio; [la⁻]_b, blood lactate concentration; f_c , heart frequency.

Significant difference; $P < 0.001$.

13.8 (±1.1) g·dL⁻¹ and 14.1 (±1.4) g·dL⁻¹, for Hct 43.2% (±1.0%) and 45.5% (0.9%) for the strength and control group, respectively. Values from the pretests are presented in Table 1.

DISCUSSION

The results from the present study demonstrate that movement specific and high-intensity strength training improves upper body endurance performance by improved work economy. The criterion measure of upper body endurance capacity was time to exhaustion, anaerobic threshold, and double-poling economy during a double-poling ergometer test. Because the control group was engaged in a period of training in preparation for the upcoming ski season, it is not surprising that also their performance on the ski-specific test to exhaustion improved over the 9 wk. Time to exhaustion in the control group increased by 57%. In contrast, the strength-training group extended their performance time by 136%. The difference in improvement in time to exhaustion, 79%, between the strength and control group, is assumed to be a result of the maximal strength training. The differences in time to exhaustion between the two groups and the magnitude of improvement for the strength group were larger compared with a similar study (11) using well-trained male cross-country skiers. In that study, the increases in time to exhaustion were 47% and 25% for the strength and control group, respectively. This would seem only partially explained by the fact that 88% of the planned strength training were performed in the present study compared with 75% in the previous study (11). The preintervention level of maximal strength was relatively lower for the female cross-country skiers in the present study. Thus, the increase in maximal strength may have a more pronounced effect upon female cross-country skier's endurance performance.

The 15% increase in 1RM was in accordance with results from a previous study (11). We consider the increase in maximal strength reasonable considering that a very low volume of strength training was performed. Compared with former studies (14,15), the improvement in 1RM was smaller in the present study. This may be due to differences in muscle mass involved and muscle fiber type distribution (1), even though this was not tested in any of the studies. As suggested by Sale (21) and Schmidtbleicher (25), the present strength training regimen improved 1RM as well as time to peak force at 60% and 80% of 1RM. The two groups did not differ in time spent performing strength training. No

changes in 1RM or any of the force parameters for the control group should call into question their strength training regimen, which is the one normally used by cross-country skiers. Training with low loads and high numbers of repetition is more likely to be endurance than strength training in the muscles involved, especially for these trained athletes. Another explanation could have been lack of specificity in their strength training. The control group was not restricted from specific strength training, provided that they performed at least 20 repetitions, as they normally do. Therefore, this should not be a cause for lack of improvement in 1RM and force parameters.

Sometimes it might be advantageous to overcome resistance with the greatest possible speed at the beginning of the movement, when the external load is low and the duration of the movement is short. In such cases, the influence of maximal strength is diminished and the importance of the rate of force development increases. Poling at high speeds on flat terrain is an example of such a situation, and this property seems more important in cross-country skiing after the introduction of the skating techniques with high racing speeds. Time to peak force decreased at the last repetition of a 20-repetition test at 60% of 1RM for the strength group. In addition, decreased time to peak force during the test to exhaustion on the ski ergometer shows that the present maximal strength training improves the ability of rapid force development even when the musculature performs repetitive poling cycles at high power outputs. This is in line with data from Behm and Sale (2). It is important to underline that during strength training, it is the speed of contraction that is fast, not the movement speed. Thus, the movement speed is not as important, and the use of light weights that could lead to high movement velocities and injuries due to momentum does not have to constitute the only means of improving power. There was a correlation between 1RM and time to peak force working on the ski ergometer ($r = -0.78$, $P < 0.01$) and between improvement in 1RM and improvement in double-poling economy ($P = 0.67$, $P < 0.05$) as well as between time to peak force ($r = 0.86$, $P < 0.01$) and reduced relative force employed ($r = 0.81$, $P < 0.01$) working on the ski ergometer and double-poling economy. These results suggest that an increase in specific maximal strength combined with specific endurance training leads to improved double-poling economy. Improved double-poling economy at maximal aerobic velocity extend the duration of time to exhaustion. The improvement in double-poling economy was not associated with changes in peak-poling force or poling frequency. It appears that one of the major changes was a decrease in the time to peak force during double poling. Decreasing time to peak force working on the ski ergometer without changing the poling frequency at a standard workload results in longer rest periods between strokes and may enhance blood perfusion in the muscle resulting in better mechanical efficiency during exercise.

What then could explain the control groups improvement in the test to exhaustion? It would have been natural to expect improved double-poling economy due to 5 wk of specific training. This did not happen, and one could then

suspect a learning effect on the ski ergometer to be the cause for their improvement in time to exhaustion, but then one could again expect an improved poling economy. Considering the results from a previous study (30), a learning effect is not assumed to be the reason behind the improved time to exhaustion for the control group. The most probably reason for improvement caused by their strength and endurance training is the ability to work for an extended period of time with relatively high levels of blood lactate acid.

The conductance theory (27) suggests that oxygen consumption in small muscle mass activities is limited by peripheral factors such as quantity of muscle-mass involved, restricted capillary density, the mean transit time of muscle blood flow, and oxidative capacity. At maximal work, the muscle mass involved in double poling in cross-country skiing might be too small to receive all blood pumped to the working muscles. When supplying a small muscle mass and, thereby, a small capillary net, the heart must work against a large peripheral resistance (5,26). Contractions using more than 15% of maximal strength limit blood flow via vaso-compression, and use of more than 70% of maximal voluntary contraction can transiently occlude the capillaries, blocking blood flow entirely (27). The reduction of the percentage usage of maximal force involved in double poling from 43.7% to 28.5% for the strength group, due to increased level of maximal strength, may have facilitated work economy and endurance time via enhanced blood flow. If this is correct, one theoretically could have expected a reduction in $[La^-]_b$ at the post test for the strength group. On the other hand, logically, a reduction in $[La^-]_b$ was not expected because they probably did not lose their ability to push themselves as long as possible at this standard exercise intensity. A lower $[La^-]_b$ for the strength group could have been expected if measuring the $[La^-]_b$ at the same time at the pre- and post-test. If an increased level of maximal strength led to enhanced blood flow after the strength training period, one could then have expected higher $\dot{V}O_{2peak}$ for the strength group compared with the control group. A reason that this did not happen may be that further improvement in maximal strength is needed to give perfusion conditions, which could have significant effect upon $\dot{V}O_{2peak}$. This assumes the strength level of the musculature to be a limiting factor of $\dot{V}O_{2peak}$. Another and probably more factor-limiting $\dot{V}O_{2peak}$ is a limited capillary net and oxidative capacity in the upper body musculature. Further studies are needed to elucidate the perfusion conditions in the musculature during upper-body work in cross-country skiing.

No changes in $\dot{V}O_{2max}$ and Th_{an} measured while running on the treadmill were expected because the endurance training the last 5 wk of the experimental period were dominated by roller skiing and skiing. Because of this, it would have been reasonable to expect improvement in $\dot{V}O_{2peak}$, $Th_{an,ski}$, and the ratio between $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$. A reason for why this did not happen might be that the volume and/or the quality of endurance training performed by the subjects were too low. The subjects' endurance training were dominated by long-distance training and little high-intensity training, which is the one presumably leading to improved

$\dot{V}O_{2peak}$ and $Th_{an,ski}$ of well-trained subjects (1). An additional explanation might be that the 5-wk period of specific endurance training was too short to induce changes in these mentioned parameters. In the present study, Th_{an} for all subjects corresponds to 84% of $\dot{V}O_{2max}$ or 91% of f_{cmax} in accordance with results reported in previous studies (10,31) on well-trained athletes. $Th_{an,ski}$ for all subjects occurred at 86.3% of $\dot{V}O_{2peak}$ or 92.3% of f_{cpeak} , in line with results in a previous study (31).

The correlation between $\dot{V}O_{2max}$ and $\dot{V}O_{2peak}$ was in contrast to previous studies on male cross-country skiers (18,30,31). The reason for this might, again, be that only 5 wk of specific endurance training had been performed and that the endurance training performed in the months before the experiment were, by environmental causes, dominated by running.

In most studies combining strength and endurance, the subjects training for both are exposed to a greater total training volume compared with the subjects training only for strength or endurance. Overtraining might cause a detrimental effect when combining the training regimens. Nelson et al. (19) claimed that simultaneous training of strength and endurance inhibits the normal adaptation to either training regimen when performed alone. A more interesting question for the endurance athlete is how maximal strength training affects the endurance performance because both capacities are needed. There is also a question how to define aerobic endurance. More studies might have found positive effect from strength training upon endurance performance if considered working economy and time to exhaustion as important factors. In the present study time to exhaustion at standard workload is regarded as an important integrated measure of aerobic endurance. At the post test, subjects time to exhaustion is close to the time spent during a 5-km race.

CONCLUSIONS

It is concluded that maximal strength training in the upper-body improve the double-poling performance by improved work economy. Work economy was improved by a reduction in relative workload and time to peak force while double poling. Time to peak force and reduction in relative force employed working on the ski ergometer correlated both with time to exhaustion and double-poling economy. The results showed considerable potential for improvement in 1RM and time to peak force even when the strength training is superimposed on a relative large volume of endurance training.

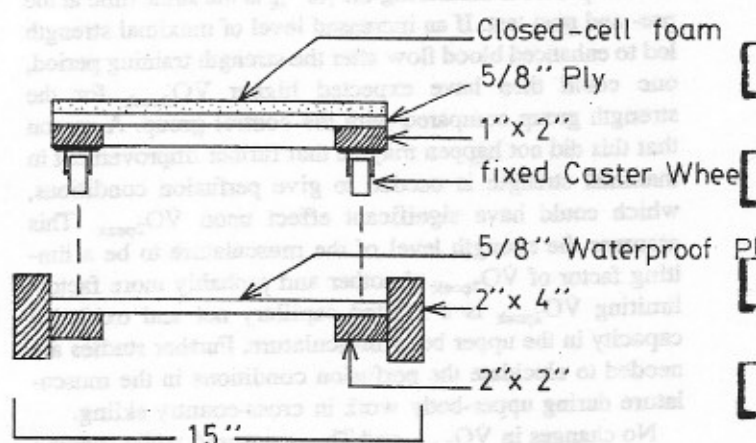
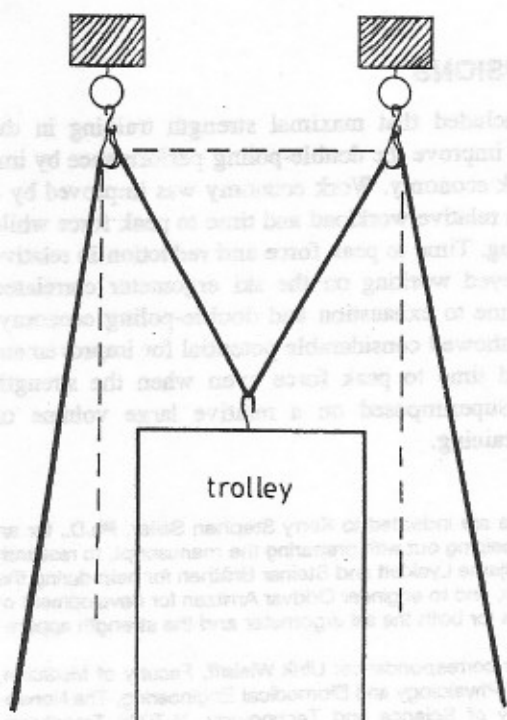
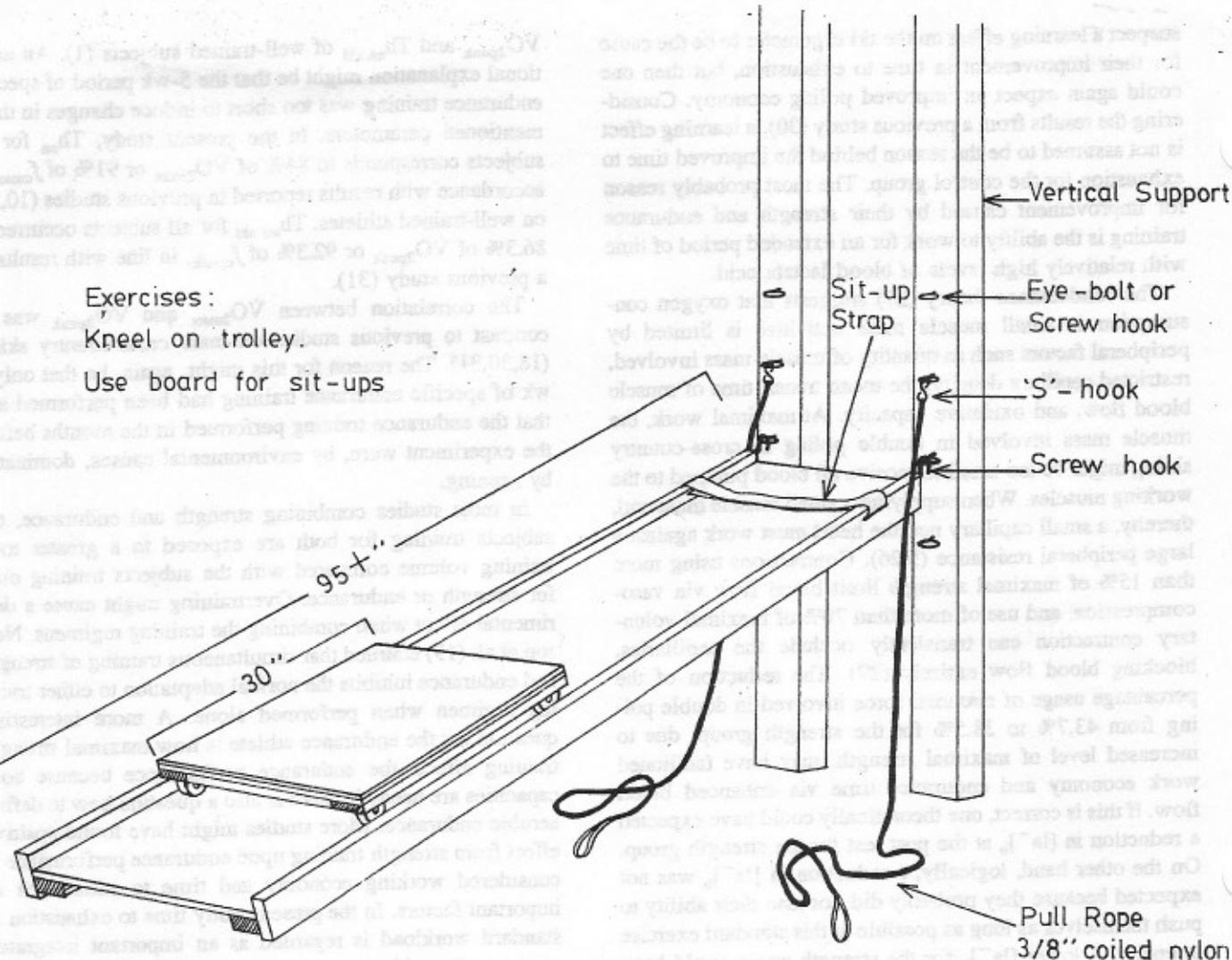
The authors are indebted to Kerry Stephen Seiler, Ph.D., for an excellent job helping out with preparing the manuscript, to research fellows Olav Bjarne Lysklett and Steinar Bråthen for help during the data collection, and to engineer Oddvar Arntzen for development of data programs for both the ski ergometer and the strength apparatus.

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Exercises:

Kneel on trolley.

Use board for sit-ups



— Alternate pull-rope pattern:

— rope hooks directly to trolley via pulleys on support