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The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers

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Aim: **To investigate the effect of supplementing high-volume endurance training with heavy strength training on muscle adaptations and physical performance in elite cross country skiers. Eleven male (18–26 years) and eight female (18–27 years) were assigned to either a strength group (STR) (*n* = 9) or a control group (CON) (*n* = 10). STR performed strength training twice a week for 12 weeks in addition to their normal endurance training. STR improved 1 repetition maximum (RM) for seated pull-down and half squat (19 ± 2% and 12 ± 2%, respectively), while no change was observed in CON. Cross-sectional area (CSA) increased in m. triceps brachii for both STR and CON, while there was no change in the m. quadriceps CSA. VO_{2max} during skate-rollerskiing increased in STR (7 ± 1%), while VO_{2max} during running was unchanged. No change was observed in energy consumption during rollerskiing at submaximal intensities. Double-poling performance improved more for STR than for CON. Both groups showed a similar improvement in rollerski time-trial performance. In conclusion, 12 weeks of supplemental heavy strength training improved the strength in leg and upper body muscles, but had little effect on the muscle CSA in thigh muscles. The supplemental strength training improved both VO_{2max} during skate-rollerskiing and double-poling performance.**

Cross country skiing, including both sprint skiing and traditional races, is a typical endurance sport with a high reliance on maximal aerobic power. However, the introduction of sprint skiing and mass start competitions has increased the importance of other physiological factors affecting top speed on skis, such as muscular strength and the ability to generate high power (Stöggl et al., 2007a, b). Consequently, heavy strength training has gained interest both in science and in the practice of cross country skiing athletes. In fact, a strong correlation has been reported between maximal power output measured in a 4 repetition maximum (RM) rollerboard test and sprint skiing tests in cross country skiing (Stöggl et al., 2007a). Further, a strong correlation has also been found between maximal speed and performance in short duration tests in running and cross country skiing (Rusko et al., 1993; Stöggl et al., 2007a, b). In addition to potentially having a role in maximal power generation and top speed on skis, heavy strength training may also reduce the energy cost of skiing. However, this has only been investigated during double poling in an ergometer, which may be different from skiing (Hoff et al., 1999, 2002; Østerås et al., 2002).

It has been suggested that supplementing endurance training with maximal strength training does not increase muscle mass in cross country skiers (Hoff et al., 1999, 2002; Østerås et al., 2002; Nesser et al., 2004; Welde et al., 2006). However, muscle mass was not measured in these studies; the suggestion was inferred from the fact that no change in bodyweight was observed. In general, strength training two to three times per week for 10–12 weeks, with training loads above 60% of 1RM and two to six series per exercise, normally results in a considerable increase in muscle strength and the cross-sectional area (CSA) of the trained muscle groups (Campos et al., 2002; Rhea et al., 2003; Peterson et al., 2004; Wernbom et al., 2007). A 40% improvement in 1RM is normally observed in untrained subjects after a strength training program lasting 12 weeks (Kraemer et al., 2002). However, high-volume endurance training may be antagonistic to the normal strength training adaptations on muscle size and strength, possibly causing strength gain to be reduced when strength and endurance training are performed in parallel. In fact, studies have reported only 10–40% improvement in 1RM when strength training and endurance training were combined. (Hickson et al., 1988; Hoff et al., 1999, 2002; Bishop et al., 1999; Bell et al., 2000; Millet et al., 2002). Elite cross country skiers may reach a volume of 60–90 h endurance training per month in the pre-season. Training generally includes disciplines that focus on the endurance training, including running, bicycling, and rollerskiing. Only parts of this training include arm muscles. Thus, performing strength training during a period of high-volume endurance training may negatively affect the strength gain particularly in leg muscles.

Supplementing endurance training with strength training does not appear to compromise the normal increase in VO_{2max} inflicted by endurance training (Hickson et al., 1988; Bell et al., 2000; Hoff et al., 2002). Enhanced upper body capacity, both strength and aerobic, has been recognized as an important strategy to increase complex performance in field tests in cross country skiing (Shorter et al., 1991; Terzis et al., 2006; Gaskill et al., 1999; Mahood et al., 2001; Nesser et al., 2004). However, the effect of strength training on changes in performance and VO_{2max} during whole body efforts, like skate-skiing, has not been examined in elite athletes.

Improved work economy on a double poling ergometer has been reported after a period of heavy strength training (Hoff et al., 1999, 2002; Østerås et al., 2002). However, the effect of strength training on work economy and energy consumption in skate-rollerskiing on treadmill, or in the field, has not been investigated. The aims of this study were, therefore, to examine the effect of supplementing high-volume endurance training with strength training on:

1. the Cross sectional area of thigh and arm muscles.
2. VO_{2max} during running and skate-rollerskiing, and energy consumption in submaximal skate-rollerskiing.
3. Rollerski performance during a time-trial, double-poling performance on a poling ergometer, and performance in sprint-rollerskiing.

Methods

Subjects

Eleven male and eight female competitive cross country skiers completed the study. The inclusion criteria were finishing top 30 for senior women and top 70 for senior men in the Norwegian Cross Country Skiing Championships. A criterion for junior skiers was top 15 in the Norwegian Championships for juniors. The participants were self-selected into a strength group (STR) ($n = 9$; 2 junior and 7 senior) or a control group (CON) ($n = 10$; 2 junior and 8 senior). None of the skiers performed strength training systematically before entering the study. A total of 11 females and 14 males started the study, but six participants were excluded from the study due to injuries, illness or inability to complete the required number of strength training sessions (minimum 85% adherence). The athletes' physical characteristics are shown in Table 1. The study was approved by the Regional Ethics Committee of Southern Norway and performed according to the Declaration of Helsinki. The subjects gave their written consent before study participation.

Intervention

The strength training program lasted for 12 weeks from the beginning of June to the end of August, a basic preparatory training period for cross country skiers. STR performed two strength workouts per week in June and August, and one workout per week in July. Exercises were performed in the same order at each training session: half squat, seated pull-down, standing double-poling and triceps press (Fig. 1). Subjects performed a general aerobic warm up for 10 min followed by three submaximal series (10-6-3 reps) with increasing loads (40%, 60%, and 80% of 1RM) in half squat, before beginning the maximal half squat sets. For the other exercises, one warm-up set per exercise (three repetitions, 80% of 1RM) was performed before the maximal sets. Rest between sets was set to 2–3 min. The training sessions lasted approximately 45 min. When a subject could successfully execute three or four sets with the prescribed load, the load was increased by 2.5–5% at the next session. Standing double-poling was performed with 10RM load throughout the intervention period because it was difficult to perform this exercise with the correct technique with higher loads. The upper body exercises targeted specific muscles used in cross country skiing. All upper body exercises utilized a handlebar specifically designed to imitate the grip on poles in cross country skiing. Free weights were used in the half squat during training.

The strength training program was designed as a "daily undulating periodized program," with progression in intensity (Table 2). These methods to vary the strength training load have been shown to be effective in increasing strength (Willoughby, 1993; Rhea et al., 2002). The aim of the strength training regime was to increase the cross-sectional area of targeted muscles, and further increase strength, as described in

Table 1. Main characteristics of the two groups (mean ± standard deviation)

	STR			CON		
	Women ($n = 3$)	Men ($n = 6$)	Total ($n = 9$)	Women ($n = 5$)	Men ($n = 5$)	Total ($n = 10$)
Age (year)	21.3 ± 5.1	21.2 ± 2.5	21.2 ± 3.2	22.6 ± 2.4	20.8 ± 2.5	21,7 ± 2.5
Height (cm)	166.0 ± 3.6	182.0 ± 4.3	176.7 ± 8.9	168.6 ± 6.5	178.0 ± 3.6	173.3 ± 7.0
Weight (kg)	60.1 ± 10.1	77.1 ± 3.4	71.4 ± 10.2	60.1 ± 7.5	75.5 ± 7.1	67.8 ± 10.6
VO_{2max} – running (mL/kg/min)	61.5 ± 1.1	67.3 ± 5.1	64.7 ± 4.9	57.9 ± 2.8	69.5 ± 4.7	64.6 ± 7.1
VO_{2max} – skating (mL/kg/min)	56.8 ± 1.6	64.4 ± 5.1	61.6 ± 5.5	53.1 ± 3.0	68.3 ± 6.1	62.0 ± 9.2
1RM seated pull-down	26.7 ± 8.0	43.8 ± 2.6	38.3 ± 9.4	27.0 ± 3.3	38.8 ± 3.2	33.5 ± 7.7
1RM half-squat	108.3 ± 25.2	159.2 ± 16.3	139.4 ± 32.9	90.0 ± 11.2	152.0 ± 21.8	121.0 ± 36.7

No significant differences between groups in total or between groups when divided into gender.
STR, strength group; CON, control group; RM, repetition maximum.

Fig. 1. Strength exercises and tests (a) standing double poling, (b1) and (b2) seated pull-down [training and 1 repetition maximum (RM) test], (c) triceps press, (d1) half squat with free weights (training) and (d2) in Smith-machine (1RM test).

Table 2. Strength training program for STR

Week	1–3	4	5–8	9–12
Workouts per week	2	2	1	2
Sets × repetitions	Day 1: 3 × 6RM Day 2: 3 × 10RM	Day 1: 3 × 5RM Day 2: 3 × 8RM	Day 1: 4 × 8RM	Day 1: 3 × 4RM Day 2: 3 × 6RM

STR, strength group; RM, repetition maximum.

previous studies (Campos et al., 2002; Kraemer et al., 2002). Training for low back and abdominal muscles was optional for both groups. The normal endurance training was managed by the athletes themselves or after consulting with their coach. Subjects recorded each training session throughout the 12 weeks using a training log that was sent by e-mail to the project coordinator. Subjects were individually supervised at the three first strength training sessions by an investigator in order to ensure proper technique and appropriate work load.

Testing procedures

Before the pre-test at the start of the intervention, all subjects completed one familiarization trial on the rollerski treadmill, double-poling ergometer, and in the strength tests. All subjects were familiar with the VO_{2max} running test and outdoor rollerskiing. The entire battery of tests, including a rest day, was conducted over 4 days (Table 3). All test procedures, including the order of tests, were identical at pre- and post-test. During the test days, athletes were allowed to drink a sports drink *ad libitum*, and a light meal was consumed between tests on the heaviest test day (test day 3).

Testing of counter movement jump performance (test day 1)

Counter movement jumps (CMJ) were executed on a force platform (SG 9; Advanced Mechanical Technology Inc., Newton, Massachusetts, USA) and force data were processed through a low pass filter at 1050 Hz. The subjects warmed up with 5 min cycling on an ergometer at 60–70% of maximal heart rate (HR_{max}). The CMJ started from a standing position with hands placed on the hips and the counter movement was performed as one rapid movement down to a self-selected depth. Subjects used their own shoes at pre- and post-test. Jump height was calculated from the vertical reaction force impulse during take off. Subjects performed four jumps at pre

Table 3. The entire test-battery including time for each exercise and total time each test day

	Test battery	Time (min)	Total time (min)
Test day			
1	(1) CMJ	10	120
	(2) Work economy and VO_{2max} during skate-rollerskiing	50	
	(3) Body composition	60	
2	VO_{2max} during running	30	30
Rest day			
3	(1) 100-m sprint skiing test	30	105
	(2) 1RM strength tests	30	
	(3) Break	20	
	(4) Double-poling performance	25	
4	Rollerski time-trial	100	100

CMJ, counter movement jumps; RM, repetition maximum.

and at post-test, and the best result was used in the data analysis (CV < 5%).

Work economy and VO_{2max} during skate-rollerskiing (test day 1)

Oxygen consumption was measured by an automatic system (Oxycon Pro Jaeger Instrument, Hoechberg, Germany) that was calibrated according to the instruction manual before each test. Oxygen and CO_2 analyzers were calibrated with room air and certified calibration gases at 180 kPa (5.55% CO_2 and 94.45% N_2). The flow turbine (Triple V; Erich Jaeger GmbH, Hoechberg, Germany) was calibrated with a 3.00 L 5530 series calibration syringe (Hans Rudolph Inc., Kansas City, Missouri, USA). Heart rate (HR) was measured using Polar S610i™ (Polar electro OY, Kempele, Finland) and blood lactate concentration was measured in unhemolyzed blood from capillary fingertip samples (YSI 1500 Sport; YSI Incorp., Yellow Spring Instr. Co., Inc., Yellow Springs, Ohio, USA).

Swenor skating rollerskis (Swenor, Sarpsborg, Norway) with type 1 wheels were used during warm up and testing. The same pair of rollerskis was used during pre and post tests and the same pair was also used during warm up to ensure stabilization of the friction in the wheels. Swix Star poles (Swix, Lillehammer, Norway) with a tip customized for treadmill rollerskiing were used. The V1 skating technique with optional hangarm, was used for both submaximal and VO_{2max} testing.

Work economy and VO_{2max} tests during rollerskiing were performed on a treadmill with belt dimensions of 3×4.5 m (Rodby, Sodertalje, Sweden). After a 15 min warm up (60–70% of HR_{max}) on the treadmill the subjects completed 3×5 min bouts with a 2 min break between each effort. The speed on the treadmill, at submaximal tests was set to 3 m/s for men and 2.5 m/s for women, with inclines of 4°, 5°, and 6° for both genders. Oxygen consumption and HR were averaged between 2.5 and 4.5 min. Blood plasma lactate concentration was measured immediately after each 5 min effort. Eight minutes after the last submaximal effort, the participants performed a VO_{2max} test. The subjects started at 5° or 6° inclination, and the speed was set to 3 m/s for men and 2.5 m/s for women. With constant speed, the inclination was increased by one degree every minute until 8°, and thereafter the speed was increased with 0.25 m/s until exhaustion. Respiratory exchange ratio > 1.1 and skiing to exhaustion were used as criteria to indicate that VO_{2max} was reached. Oxygen consumption was measured continuously and averaged over 1 min, and the highest oxygen value was considered as VO_{2max}.

Body composition (test day 1)

The subject's bodyweight was measured before each treadmill test (Seca, model 708 Seca, Germany). After the treadmill test, magnetic resonance tomography (MR) was performed. MR (MR GE Signa HD 1.5 T, Waukesha, Wisconsin, USA) was performed with the feet strapped and elevated on a pad. The machine was centered 2/3 distal at femur. Nine cross-sectional images were taken in a regular manner from the patella against the iliac crest (5 mm cross section with a spacing of 35.5 mm) to measure CSA of m. quadriceps. Both legs were measured and the mean value of the two legs was used in the data analysis. During the scanning of muscles in the dominant arm, the arm was stretched behind the head, and the body was placed so that the dominant arm was centered in the middle of the machine. Nine cross-sectional images from the caput humeri against the elbow joint were taken (5 mm cross section with a spacing of 30 mm) to measure CSA of m. triceps brachii. Only the dominant arm was analyzed. The images were then conveyed to a computer for further analyses. The circumference of m. quadriceps and m. triceps brachii was measured on all images, and the average circumference from the nine images is used in the results. Changes in body composition were measured by Dual Energy X-ray Absorptiometry (GE Medical system, Madison, Wisconsin, USA). The participants were not allowed to eat or drink the last two hours before each DEXA scan.

VO_{2max} during running (test day 2)

Oxygen consumption during treadmill (Woodway GmbG, Weil am Rein, Germany) running was measured with the same equipment as during rollerski treadmill testing. After a standardized 20 min warm up, subjects ran at a constant 10.5% incline, while the speed was increased incrementally each minute until exhaustion. Women ran from 8 to 12.5 km/h, whereas men ran from 10 to 14.5 km/h (with individual variations). Respiratory exchange ratio > 1.1 and running to exhaustion were used as criteria to indicate that VO_{2max} was reached. Oxygen consumption was measured continuously and the highest oxygen value averaged over 1 min was considered as VO_{2max}.

100-m-sprint skiing test (test day 3)

Subjects warmed up for 10 min by running (~ 65% of HR_{max}) and then 10 min on the testing rollerskies (65–75% of HR_{max}). Testing was conducted on an even, straight and flat asphalt road using Swenor skating skis with wheel type 1. All participants used the same physical pair of skis, but used their own boots and skating poles fitted with rollerski tip. The participant's time and speed over 100 m was measured with photocells every 20 m (JBL Systems, Oslo, Norway). Maximal velocity (V_{max}) was defined as the subject's highest speed (m/s) during the 100-m test. Subjects performed two trials in both directions on the road in a freely chosen skating technique. The mean of the best result for each direction was used for further analyses. A wind gauge (Sports Anemometer; Gill instruments Limited, Hampshire, England) detected the wind speed. At pre-test, two subjects performed with wind at >2 m/s, while the other subjects performed at <2 m/s. At post-test, the wind was <2 m/s for all subjects. The road was dry on all test days while the temperature was between 11° and 18°.

1RM strength tests (test day 3)

The 1RM tests for seated pull-down and half squat exercises (Fig. 1) were performed after the sprint skiing test. In both exercises, the subjects performed three sets of exercise-specific warm up with gradually increasing load (10 repetitions at 40%, six repetitions at 75% and three repetitions at 80% of the expected 1RM). The first attempt for both exercises was performed with a load approximately 5% below the expected 1RM. After each successful attempt, the load was increased by 2–5% until the subject failed to lift the load after two to three consecutive attempts. The rest period between each attempt was 2–4 min. The order of tests was the same in all testing sessions. All 1RM testing was supervised by the same investigator and conducted on the same equipment with identical equipment positioning for each subject. The 1RM half squat was performed in a Smith machine (Tecnogym 2SC multipower, Gambettola, Italy). At the familiarization session, the correct depth (90° knee angle) was noted for reproduction. The position of the feet was marked and the correct depth was controlled with an elastic band. The movement over the knee joint was standardized in the sagittal plane by moving the knees over toes. For the seated pull-down, a Tecnogym Radiant (Tecnogym, Gambettola, Italy) apparatus was used. The movement started with the handlebar positioned at the same height as the forehead. The participants then pulled the handlebar down to the hip bone. Elbows were held slightly lateral to simulate a double-poling pull, and the wire was parallel to the back support on the bench. In order for the 1RM to be accepted, the handlebar had to be pulled completely down in one continuous motion with the hands parallel (Fig. 1).

Double-poling performance (test day 3)

Double-poling performance was tested on a custom-built ergometer based on the Concept II rowing ergometer (Concept Inc., Morrisville, Vermont, USA), to simulate double poling in cross country skiing (Holmberg & Nilsson, 2008). This test was carried out after the sprint skiing test and the 1RM tests. Therefore, only a specific warm-up of 5 min double poling at $\sim 60\%$ of HF_{max} was performed in addition to two 20 s efforts at approximately 80% of maximal power. After the specific warm-up, subjects performed two 20 s bouts at maximal effort, separated by 2 min rest. The best mean power output results were used for further analyses. Before the 5 min double-poling test, the subjects had a recovery exercise for 5 min on a cycle ergometer at 100 W and 60 r.p.m. The power during the first 90 s of the 5 min double-poling test was fixed to avoid over-pacing and individually set, based on preliminary tests. Thereafter, the subjects regulated the power themselves. The resistance of the ergometer was constant for the entire duration of the test. The goal of the test was to produce as much work as possible over 5 min. During the post-test, the same procedure was followed, with the power during the first 90 s being set to the average power found at pre-test. This was to avoid a learning effect from pre- to post-test. The double-poling cycle rate was calculated using video analysis (Sony DCR-TRV900E, Tokyo, Japan).

Rollerski time-trial (test day 4)

The double-poling rollerski time-trial (1.1 km) and skate-rollerskiing time-trial (1.3 km) were performed outdoors on an uphill road. The same physical pair of rollerskis used by each subject at pre-test was also used at post-test. The rollerskis were new at pre-test and stored in a dark, dry room during the intervention period. Swenor skating skis wheel type 2 without the blocking mechanism were used for both the skate-rollerskiing and double-poling tests. Subjects warmed up with 20 min of rollerskiing and 15 min of running at 60–70% of HR_{max}. The final 5 min of the warm up were again performed on rollerskis at an individual intensity. For both time-trials, subjects started individually at 30 s intervals. The skate-rollerskiing test was performed first, with a freely chosen technique. After completion, subjects were transported by car back to the start. After a 45 min break characterized by a low-intensity activity, the double-poling time-trial commenced. The road was dry on both pre- and post-test, while temperature was 9°–13° for pre-test and 10°–16° at post-test (Table 4).

Statistics

All results are reported as means and standard error (SE) unless otherwise stated. Paired *t*-test was used for detecting significant changes from pre- to post-test within groups and unpaired *t*-test was used to detect significant differences between groups in relative changes. Pearson's product moment correlation analysis was used for correlation analyses, and sub-analysis of correlations for men and women separately were included to reveal sex differences. Statistical calculations were performed using Microsoft Excel and

Table 4. Time at time trial rollerski pre-test (min:sec ± SD)

	STR			CON		
	Women ($n=3$)	Men ($n=6$)	Total ($n=9$)	Women ($n=5$)	Men ($n=5$)	Total ($n=10$)
DP	6:11 ± 0:57	4:29 ± 0:29	5.13 ± 0:40	6:19 ± 0:39	4:31 ± 0:17	5:25 ± 1:07
Skating	5:59 ± 0:30	4:50 ± 0:19	5.03 ± 1:03	6:14 ± 0:09	4:41 ± 0:19	5:27 ± 0:50

No significant differences between groups in total or between groups when divided into gender.

DP, double poling; STR, strength group; CON, control group.

GraphPad software. A P-value ≤ 0.05 was considered statistically significant. A P-value <0.10 was considered a tendency.

Results

Endurance training during the intervention period

Training registration from the subjects training diary showed no difference in average weekly endurance training volume between the two groups (STR: 15.2 ± 1.1 h) (CON: 15.3 ± 0.7 h) during the 12-week intervention period.

Strength tests

STR increased 1RM strength in seated pull-down and half squat more than CON (Fig. 2, $P<0.01$). STRs increase was $19 \pm 2\%$ for the seated pull-down and $12 \pm 2\%$ for the half squat (both $P<0.01$). CON tended to increase 1RM in the seated pull-down ($5 \pm 3\%$ $P = 0.08$). The change in CMJ performance tended to be different between groups ($P = 0.10$) with a $6.2 \pm 2.7\%$ ($P<0.05$) decrease in CON and no change in STR ($1.7 \pm 2.4\%$, NS) (Fig. 3).

Muscle CSA and lean body mass (LBM)

CSA in m. triceps brachii tended to increase more in STR than in CON ($P = 0.10$), with a $5.5 \pm 2.1\%$

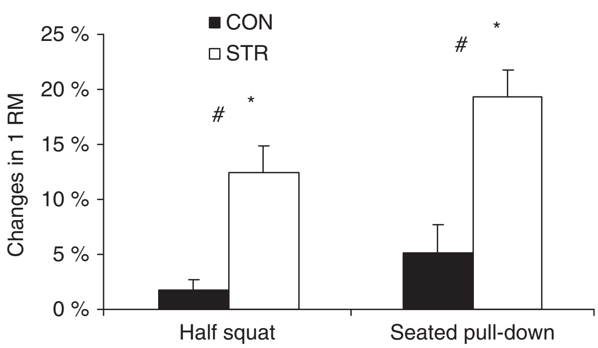

Fig. 2. Changes in 1 repetition maximum (RM) half-squat and seated pull-down. *Significant change from pre-test ($P<0.01$). # Significant change between groups ($P<0.01$).

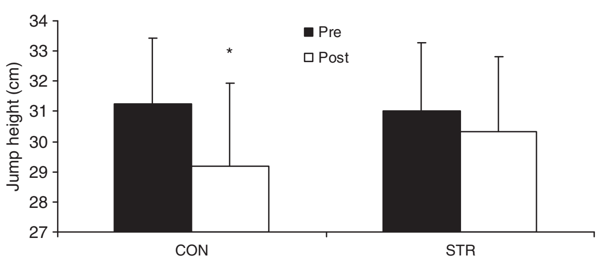

Fig. 3. Changes in counter-movement jump. *Significant change from pre-test ($P<0.05$).

($P<0.01$) increase for STR and a $1.5 \pm 0.7\%$ ($P = 0.05$) increase for CON (Fig. 4). CSA remained unchanged in m. quadriceps for both groups. The increase in leg LBM was significantly greater in CON than in STR ($P<0.05$). Total LBM and leg LBM increased in CON ($1.8 \pm 0.5\%$, $P<0.01$ and $1.9 \pm 0.9\%$, $P = 0.05$) (Fig. 5). No statistical changes between groups in upper body LBM were seen. STR increased upper body LBM ($3.0 \pm 1.1\%$, $P<0.05$), while CON showed a tendency towards increased upper body LBM ($1.8 \pm 0.9\%$, $P = 0.07$). Total body weight remained unchanged throughout the intervention period in both groups.

VO_{2max} during skate-rollerskiing and running

VO_{2max} relative to body mass during treadmill skate-rollerskiing increased significantly more in STR than in CON ($P<0.05$) (Fig. 6). VO_{2max} during skate-rollerskiing increased by $7 \pm 1\%$ for STR ($P<0.01$) and $2 \pm 2\%$ for CON. At the pre-test, both groups

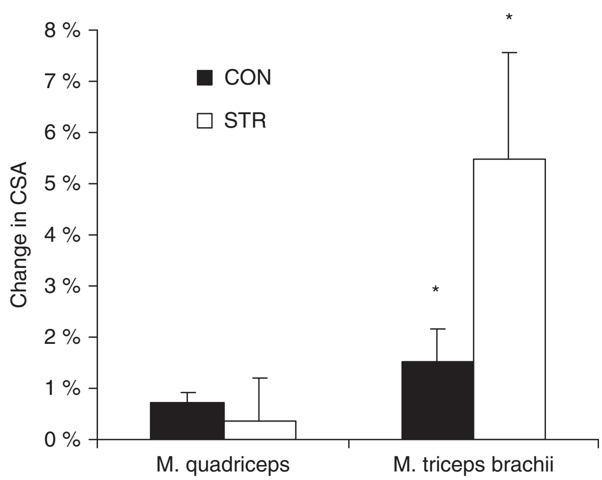

Fig. 4. Change in the cross-sectional area (CSA) of m. quadriceps and m. triceps brachii. *Significant change from pre-test ($P\leqslant 0.05$).

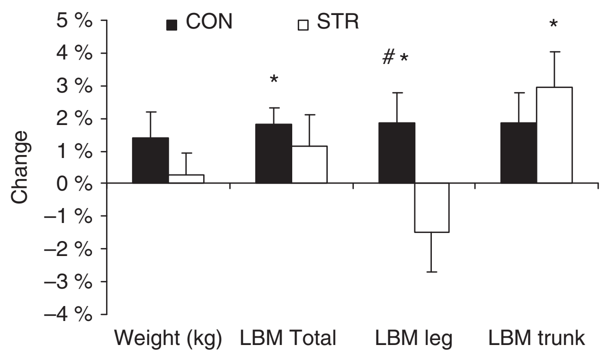

Fig. 5. Change in weight and lean body mass (LBM) measured with DEXA *Significant change from pre-test ($P<0.05$). # Significant change between groups ($P<0.01$).

had a significantly higher VO_{2max} during running than during skate-rollerskiing ($P<0.05$), while at post-test there was no difference between running and skate-rollerskiing VO_{2max} in STR, but a tendency towards higher VO_{2max} during running in CON ($P=0.07$). VO_{2max} relative to body mass during running remained unchanged in both groups.

Submaximal treadmill rollerski test

VO_2 during submaximal rollerskiing on treadmill was unchanged in both groups at all inclines. The respiratory exchange ratio was, however, reduced in STR at all inclines ($P<0.05$), while no change was observed in CON. There were no statistically significant differences between groups in HR or La^-. Average HR was reduced in STR at 4° (6.6 ± 2.7 bpm), 5° (6.9 ± 2.2 bpm), and 6° (4.7 ± 2.0 bpm) inclines (all $P<0.05$), while blood lactate concentration was decreased at the 5° incline (0.5 ± 0.1 mmol/L, $P<0.05$). In CON, blood lactate concentration was decreased at the 4° incline (0.2 ± 0.5 mmol/L, $P<0.05$) (Table 5).

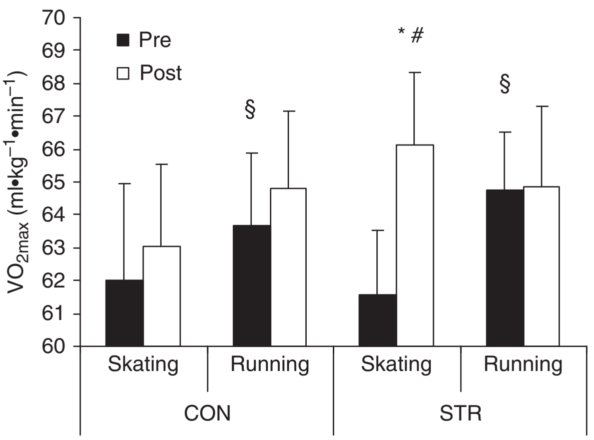

Fig. 6. Change in VO_{2max} during rollerski skating and running. *Significant change from pre-test ($P<0.01$). #Significant change between groups ($P<0.05$). §Significantly different than skating pre-test.

Rollerski time-trial performance

Rollerski time-trial performance did not change significantly between the two groups from pre-test to post-test. STR improved double-poling performance (−7.4 ± 2.6%, $P<0.05$) and slightly improved (although not significant) skate-rollerskiing performance (−3.7 ± 2.2%, $P=0.14$) (Fig. 7). CON showed significant improvement in both double-poling and skate-rollerskiing performance (−6.0 ± 1.7% and −3.3 ± 0.9%, both $P<0.05$).

Double-poling performance

Average power relative to body weight (W/kg) during the 5 min double-poling test increased more for STR than CON ($P<0.05$, Fig. 8). There were no changes in poling frequency over the intervention period within or between groups. Average poling cycle frequency at pre-test was 48.2 ± 1.1 r.p.m. in STR and 47.8 ± 0.9 r.p.m. in CON. In addition, no significant correlations were found between poling frequency and average force, 1RM results, gender or

Table 5. VO_2, respiratory exchange ratio (RER), heart rate (HR) and blood lactate (La^-) at 4°, 5° and 6° inclines with constant speed on the treadmill: 3 m/s for men and 2.5 m/s for women

	STR ($n=9$)			CON ($n=10$)		
	Pre	Post	% change	Pre	Post	% change
4°						
VO_2	41.8 (0.8)	41.9 (1.0)	0.1 (1.1)	41.7 (1.3)	41.5 (1.6)	− 0.4 (1.5)
RER	0.93 (0.2)	0.89 (0.3)	− 4.7 (1.7)*	0.92 (0.1)	0.90 (0.1)	− 1.5 (2.2)
HR	164 (2.6)	157 (2.5)	− 3.9 (1.7)*	161 (2.8)	156 (2.3)	− 2.0 (1.3)
La^-	1.6 (0.2)	1.4 (0.2)	− 8.3 (10.2)	1.4 (0.1)	1.2 (0.1)	− 8.7 (3.7)*
5°						
VO_2	48.5 (1.2)	48.3 (1.2)	− 0.3 (1.0)	48.2 (1.7)	48.0 (1.6)	− 0.2 (1.8)
RER	0.96 (0.1)	0.91 (0.2)	− 4.4 (1.5)*	0.94 (0.2)	0.93 (0.1)	− 1.4 (1.5)
HR	178 (2.1)	172 (2.2)	− 3.8 (1.3)*	173 (2.2)	170 (1.7)	− 1.3 (0.9)
La^-	2.7 (0.7)	2.2 (0.3)	− 17.1 (6.1)*	2.4 (0.3)	2.2 (0.3)	− 6.6 (4.3)
6°						
VO_2	53.6 (1.1)	54.8 (1.2)	2.3 (1.4)	54.0 (2.0)	54.4 (1.8)	0.9 (1.8)
RER	0.99 (0.1)	0.93 (0.2)	− 5.5 (1.3)*	0.99 (0.2)	0.96 (0.2)	− 2.6 (2.0)
HR	188 (2.2)	183 (1.8)	− 2.5 (1.1)*	183 (2.0)	181 (1.5)	− 0.6 (0.6)
La^-	4.4 (0.6)	3.8 (0.4)	− 10.9 (7.6)	4.4 (0.5)	4.2 (0.4)	− 3.1 (4.7)

SE, standard error. Average VO_2 (mL/kg/min) from 2.5 to 4.5 min, HR (bpm) from 2.5 to 4.5 min and blood plasma lactate concentration (mmol/L) after each bout.

*Significant difference within groups ($P<0.05$).

STR, strength group; CON, control group.

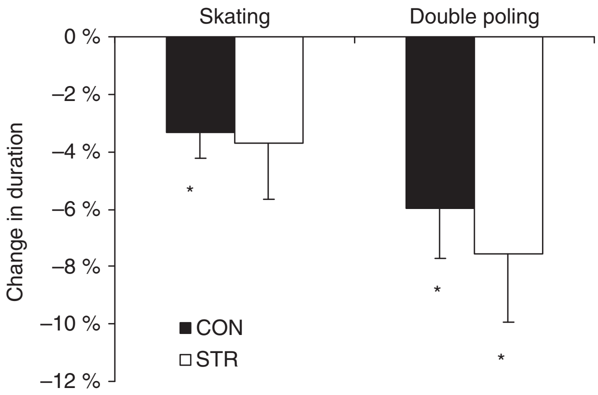

Fig. 7. Change in duration in the ski skating and double-poling time-trial tests. *Significant change from pre- to post-test ($P<0.05$).

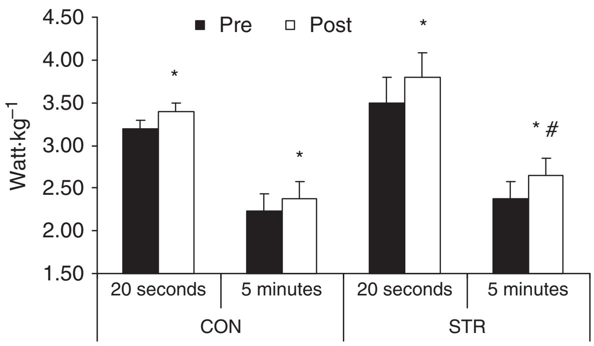

Fig. 8. Change in average relative watt (W/kg) in the 20 s and 5 min tests. *Significant change from pre-test ($P<0.01$). # Significant change between groups ($P<0.05$).

any anthropometric data. No statistically significant changes between groups were observed in average power in 20 s performance. Results from the 20 s test showed an increased power output in both STR ($8.3 \pm 2.0\%$) and CON ($6.2 \pm 1.8\%$) (both $P<0.001$).

100-m-sprint-rollerskiing

No statistically significant difference between groups was observed in 100-m-sprint-rollerskiing (Table 6). In addition, there were no statistically significant differences within or between groups after 20, 40, 60 or 80 m and max velocity. STR tended, however, to improve the 100 m time by $-1.3 \pm 0.7\%$ ($P=0.1$).

Correlation between basic tests and performance parameters

Correlation analyses from baseline ($n=25$) showed a strong correlation between 1RM seated pull-down and several performance parameters (all $P<0.01$, Fig. 9(a)–(d)). Performance on the double-poling ergometer (average power at 20 s and 5 min) correlated with the 1RM seated pull-down performance ($r=0.70$ and $r=0.87$, respectively). A correlation was also observed between double-poling and skate-rollerskiing time-trial performances and seated pull-down performance ($r=-0.81$ and $r=-0.81$, respectively). In addition, strong correlations between 1RM half squat and skate-rollerskiing time-trial performance ($r=-0.82$), and 1RM half squat and 100-m-sprint-rollerskiing performance were observed ($r=-0.89$) (both $P<0.01$, Fig. 9(e) and (f)). Separate correlation analysis for men and women demonstrated high-to-moderate correlations for women and moderate-to-low correlations for men (Fig. 9). We were not able to observe any statistically significant correlation between changes in 1RM results and changes in any of the performance tests.

Discussion

Supplementing high-volume endurance training with heavy strength training resulted in increased muscle strength in both upper body and legs. However, CSA increased only in the upper body, while no changes were detected in leg muscles. Surprisingly, for STR, VO_{2max} increased significantly during skate-rollerskiing, but did not change during running. Supplementing normal endurance training with heavy strength training for 12 weeks improved the performance in 5 min double poling on the ergometer. However, no differences between groups in the time-trial test or sprint-rollerskiing performance were detected.

The increases in 1RM seated pull-down ($19 \pm 2\%$) and half squat ($12 \pm 2\%$) for STR concur with similar studies on endurance athletes (10–40% increase over 12 weeks) (Hickson et al., 1988; Hoff et al., 1999, 2002; Bishop et al., 1999; Bell et al., 2000; Millet et al., 2002). The cross country skiers had not performed strength training systematically before, and the half squat exercise, in particular, was unfamiliar to the participants. In general, "untrained" athletes can expect to increase muscle strength by approximately 40% and "moderately trained" athletes by 20% after 12 weeks of heavy strength training, measured as 1RM in the training exercises (Kraemer et al., 2002). The relatively low strength gains observed in our skiers may be due to both the high volume of endurance training, which may have reduced the effect of strength training on the legs, and the relatively low volume of leg strength training (one exercise one to two sessions per week).

CMJ height was reduced in CON and unchanged in STR. Reduced jump height during a period of heavy endurance training involving leg muscles has

Table 6. Time at 20, 40, 60, 80, 100 m and maximal velocity (V_{max}) for rollerski skating

	STR group			CON group		
	Pre	Post	% change	Pre	Post	% change
Time						
20 m (s)	3.68 (0.10)	3.66 (0.10)	– 0.55 (0.64)	3.87 (0.08)	3.87 (0.09)	– 0.04 (0.77)
40 m (s)	6.32 (0.18)	6.29 (0.17)	– 0.36 (0.58)	6.62 (0.14)	6.60 (0.16)	– 0.30 (0.66)
60 m (s)	8.74 (0.25)	8.66 (0.24)	– 0.88 (0.62)	9.14 (0.21)	9.09 (0.22)	– 0.51 (1.17)
80 m (s)	11.08 (0.33)	10.95 (0.31)	– 1.10 (0.67)	11.54 (0.27)	11.48 (0.28)	– 0.55 (0.51)
100 m (s)	13.36 (0.40)	13.18 (0.38)	– 1.24 (0.72)	13.89 (0.33)	13.82 (0.34)	– 0.52 (0.48)
V_{max} (m/s)	8.83 (0.26)	9.00 (0.25)	2.02 (1.19)	8.55 (0.21)	8.58 (0.21)	0.38 (0.59)

STR, strength group; CON, control group.

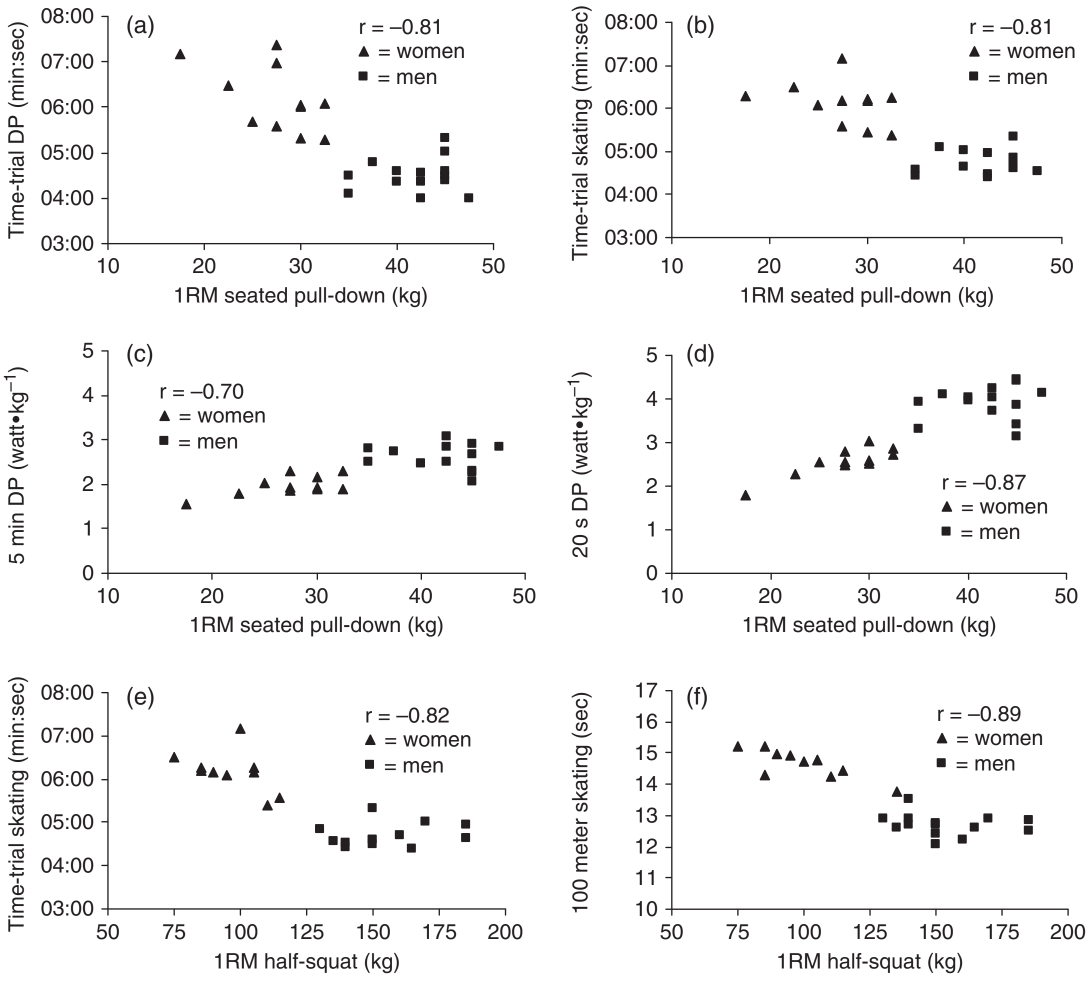

Fig. 9. Correlation between 1 repetition maximum (RM) seated pull-down and (a) rollerski double-poling time-trial (women: $r = -0.66$, $P<0.05$, men: $r = 0.13$), (b) rollerski skating time-trial (women: $r = -0.34$, men: $r = 0.08$), (c) 5 min double poling on ergometer (women: $r = 0.67$, $P<0.05$ men: $r = 0.28$) and (d) 20 s double poling on ergometer (women: $r = -0.79$, $P<0.05$ men: $r = 0.45$). (e) and (f) show correlation between 1RM half squat and rollerski skating (women: $r = -0.62$, $P<0.05$, men: $r = 0.10$) and 100 m rollerski (women: $r = -0.80$, $P<0.05$ men: $r = -0.20$). All figures show results from baseline (total $n = 25$, men $n = 14$, women $n = 11$). All values in figures show $P \leq 0.01$.

also been observed in other studies (Millet et al., 2002). Our results suggest that this "negative" effect of high-volume endurance training can be counteracted by adding heavy strength training on leg muscles. Peak leg extensor force and vertical jump height are normally highly correlated, and a concomitant increase in jumping performance with increased leg strength has been reported in several studies investigating heavy strength training (Kraemer et al., 2002). However, in the present study, the maintained jump height can be interpreted as a positive effect of strength training because of the reduced jump height observed in CON.

Strong correlations were observed between CSA in m. quadriceps and 1RM half squat ($r = 0.80$, $P < 0.01$), and between CSA in m. Triceps brachii and seated pull-down ($r = 0.91$, $P < 0.01$). This indicates that an increase in muscle CSA is an important factor for achieving further strength gains. However, CSA in m. quadriceps did not change in either CON or STR and the changes in 1RM half squat did not correlate with changes in CSA. The increased strength may alternatively be explained by improved muscle quality, improved lifting technique, and improved use of agonists, and synergists, including stabilizing muscles around spine and hip. Length alteration could also explain increased strength if the lengths of knee and hip extensors is more optimal for force generation in the critical phase of a half squat (Alegre et al., 2006). In similar studies, CSA in fiber and/or muscle circumference was unchanged (Hickson et al., 1988; Johnston et al., 1997) or increased (Sale et al., 1990; Bell et al., 1991). In the present study, STR performed a strength training program that normally results in increases in both strength and CSA (Campos et al., 2002; Kraemer et al., 2002). Thus, it seems plausible that the large volume of endurance training on leg muscles reduced the effectiveness of heavy strength training on strength gain and muscle growth. In this study, only one exercise involving leg muscles was included. However, feedback from the athletes indicated that it would be problematic to increase the strength training volume on leg muscles. Especially, problems with performing endurance training the day after heavy strength training were reported. Adding more leg exercises to the program could, therefore, have interfered more with the endurance training and compromised the quality of training. However, if the subjects had been more experienced with strength training, these issues might not have occurred. It is, therefore, likely that a higher volume of strength training can be tolerated in skiers with more strength training experience. The half squat exercise also resulted in four dropouts. Two subjects had problems with the legs ("heavy legs") and two subjects had back pain related to the half squat exercise and could therefore not complete the 12 weeks of strength training.

CSA in m. triceps brachii increased in both groups, and tended to increase more in STR than in CON ($P = 0.1$). DEXA results indicated a greater increase in upper body muscle mass for STR than for CON, a finding consistent with the changes in the 1RM seated pull-down. Increased muscle mass has, therefore, contributed to the strength gain in the upper body. These findings are also consistent with the fact that seated pull-down, in contrast to half squat, is less sensitive to changes in technique, and therefore probably more related to changes in CSA.

Surprisingly, STR increased VO_{2max} during skate-rollerskiing, a finding that contradicts similar studies, which found no further changes in VO_{2max} when strength training was added to endurance training (Hickson et al., 1988; Hoff et al., 2002; Millet et al., 2002). Before the intervention period, both groups had a significantly lower VO_{2max} in skate-rollerskiing than in running. After the intervention, VO_{2max} in skate-rollerskiing and running were similar for STR, but still lower in skate-rollerskiing for CON. This indicates that subjects in this study had insufficient technical and/or physical capacities to utilize the oxygen delivery to the upper body before the strength training. Interestingly, a lower O_2 extraction has been observed in the arms than in the legs in whole body skiing in elite athletes (Calbet et al., 2004). Results from the baseline show a strong correlation between upper body LBM and VO_{2max} during skate-rollerskiing ($r = 0.84$). Consequently, it is possible that increased upper body muscle mass contributes to increased VO_{2max} during skate-rollerskiing without affecting VO_{2max} during running. An increase in muscle strength and a concomitant improvement in skiing technique, may have improved the skiers' upper body VO_{2max} either by increased blood flow or an increased ability to extract oxygen.

No change in VO_2 during submaximal rollerskiing was observed for either STR or CON. The observed change in RER towards higher fat oxidation at a fixed intensity may contribute to delayed fatigue in long-lasting events. However, the observed changes in RER were relatively small ($<1\%$), and a small change in RER will not contribute to major changes in work efficiency as long as VO_2 is unchanged. The concomitant reductions in La^- and HR may be a consequence of the higher skate-rollerskiing VO_{2max}. The unchanged work economy in skate-rollerskiing after strength training in the present study contradicts studies by Hoff et al. (1999, 2002), who showed a large (47–136%) improvement in a time to exhaustion test after heavy strength training. However, Hoff et al. (1999, 2002) tested performance as time to exhaustion on a double-poling ergometer. In the present study, work economy was tested on a rollerski treadmill, which more closely simulates actual skiing, an exercise well known by the subjects.

Both groups significantly improved their time in the rollerski double-poling time-trial, but STR's improvement in skate-rollerskiing was not statistically significant. For reasons that are not clear, at post-test one subject in STR performed substantially slower in the skate-rollerskiing time-trial, and performed poorly in several other post-tests. By excluding this subject's results from the analyses, significant time improvement in skate-rollerskiing was achieved by STR, and the improvement tended to be greater for STR than CON ($P = 0.06$). The improved performance for both groups is probably caused primarily by the regular endurance training performed during the intervention period. STR's tendency for superior improvement can be explained by the increased VO_{2max} in skate-rollerskiing seen during treadmill testing. Correlation analyses from baseline showed a moderate correlation between 1RM seated pull-down and time-trial double poling test for the women, while a low correlation was observed for the men. Women in this study had also a significantly lower strength in both seated pull-down and half squat than men. Based on these correlations, it could be hypothesized that weaker skiers will be more likely to increase performance than stronger athletes when adding strength training to their normal training routines. However, because of the low number of skiers in STR, we were not able to compared changes in performance between weak and strong skiers. Interestingly, there was no correlation between relative muscle strength and performance in the time-trials.

Average power in the 5 min double-poling test increased more in STR than in CON. Results from baseline tests showed a significant correlation between average power in ergometer and double poling performance on rollerskis ($r = -0.89$). However, the improvement in double poling time-trial performance, which had approximately the same duration (~ 5 min), was not superior in STR. In addition, in the outdoor time-trial test, confounding elements like weather, surface and unaccustomed rollerskis may give rise to larger variations in performance. Consequently, it is harder to find intervention effects. On the other hand, the double-poling technique on the ergometer is different from double-poling on rollerskis. The strength training intervention, including seated pull-down, is more similar to the ergometer test and might influence the technique in ergometer double-poling, and thereby more positively affect ergometer performance than rollerski performance. Surprisingly, no statistical difference was found between the two groups in the 20 s test. Baseline results showed a high correlation between 1RM seated pull-down and 20 s double-poling power; thus, it was expected that increased upper body strength would improve power in the 20 s double-poling test. However, it was difficult to maintain good technique on the ergometer when performing with maximal effort; hence, technical aspects might explain the lack of transference from increased strength to performance in this test. In addition, correlation values from baseline at the 20 s test is high mainly due to the women included in this study. Consequently, strength training might be more adequate regarding performance in this test for the women because of the lower strength values at baseline.

A high correlation has been reported between maximal power output measured in a 4RM roller-board test and sprint-rollerskiing tests (50 and 1000 m) (Stöggl et al., 2007a). In the present study, baseline results also showed a high correlation between 1RM seated pull-down and 100 m sprint-rollerskiing ($r = -0.92$, $P < 0.01$, women: $r = -0.65$, men: $r = -0.57$, both $P < 0.05$), and between half squat and 100 m sprint-rollerskiing ($r = -0.89$ $P < 0.01$, women: $r = -0.80$, $P < 0.05$, men: $r = -0.20$). Twelve weeks of heavy strength training also tended to reduce the 100-m time by $-1.3 \pm 0.7\%$ ($P = 0.1$). Peak velocity during skate-rollerskiing is high and increased strength was expected to have more impact on the acceleration phase than peak velocity. However, no significant improvement was observed in the 20 m time or in V_{max} (80–100 m), a finding that could be explained by the fact that sprinting on rollerskis is highly technically demanding, especially at maximal speeds (~ 8.5–9 m/s). In previous studies, strong correlations have also been found between maximal speed and performance in short duration tests in running and cross country skiing (Rusko et al., 1993; Stöggl et al., 2007a, b). In the present study, a moderate correlation was found between the 100-m sprint rollerskiing and the performance in the time-trial skating test for women ($r = 0.62$, $P < 0.05$), while no correlation was found for men ($r = -0.16$). Weaker correlations between maximal speed and time-trial performance observed in the present study might be due to the uphill terrain, the use the skating technique, and a longer duration in the time-trial tests than in previous studies.

Perspectives

The results from this study showed increased strength, increased average power in a 5 min double-poling test, and increased VO_{2max} in a specific rollerski test after adding heavy strength training to normal endurance training in elite cross country skiers compared with a control group that only performed endurance training. However, there were no statistical differences between groups in the time-trial tests on roller skies. This indicates that we must be cautious when we try to translate improvement from one type of exercise into a sport-specific performance, even though the exercises include major parts of the sport movements. In addition, it may take more than 12 weeks to utilize the increased strength to improved performance in a complex exercise, such as cross country skiing, and longterm experiments, perhaps over several years, may be needed.

There was a moderate correlation between muscle strength (1RM) and roller ski performance (time-trial) for the women, while no correlation was observed for the men. The women were also weaker. Based on the correlation analyses, it could be argued that weaker subjects, in this study the women, could benefit from adding heavy strength training to their normal training. Further, this may indicate that there is a threshold for strength levels necessary for optimal performance in cross country skiing and suggests that strong athletes may focus on training models other than heavy strength training (with the goal of maintaining, not increasing, strength), while weaker athletes may benefit from increasing muscle strength.

Key words: cross country skiing, strength training, sprint skiing.

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