Effect of heavy strength training on muscle thickness, strength, jump performance and endurance performance in well-trained Nordic Combined athletes

Running head: *“Strength training in Nordic Combined”*

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ABSTRACT

The purpose of the present study was to investigate the effect of supplemental heavy strength training on muscle thickness and determinants of performance in well-trained Nordic Combined athletes. Seventeen well-trained Nordic Combined athletes were assigned to either usual training supplemented with heavy strength training (STR; n=8) or to usual training without heavy strength training (CON; n=9). The strength training performed by STR consisted of one lower body exercise and two upper body exercises [3-5 repetition maximum (RM) sets of 3-8 repetitions], which were performed twice a week for 12 weeks. Architectural changes in *m. vastus lateralis*, 1RM in squat and seated pull-down, squat jump (SJ) height, maximal oxygen consumption (VO_{2max}), work economy during submaximal treadmill skate rollerskiing, and performance in a 7.5 km rollerski time trial were measured before and after the intervention. STR increased 1RM in squat and seated pull-down, muscle thickness, and SJ performance more than CON ($p<0.05$). There was no difference between groups in change in work economy. The two groups showed no changes in total body mass, VO_{2max}, or time trial performance. In conclusion, 12 weeks of supplemental strength training improved determinants of performance in Nordic Combined by improving the athletes' strength and vertical jump ability without increasing total body mass or compromising the development of VO_{2max}.

Key words: Concurrent training, Endurance performance, Jumping performance, Muscle hypertrophy, Weight training

Introduction

Nordic Combined is a sport that includes both ski jumping and cross-country skiing, forcing the athletes to combine skills from both ends of the endurance-strength continuum to achieve success. Endurance training is logically the main focus when the aim is to improve the cross-country skiing performance part of Nordic Combined. Endurance training primarily affects aerobic capacity, often measured as maximal oxygen uptake (VO_{2max}), with minimal, or even negative, effects on muscle strength (Nader 2006). On the other end of the exercise intensity continuum, the Nordic Combined athletes have to focus on their explosive force-generating capacity to optimize ski jump performance. This typically involves strength training which primarily affects muscle strength and power with minimal effects on VO_{2max} (Nader 2006). Consequently, the main challenge for Nordic Combined athletes is to optimize the development of high skills in both ends of the endurance-strength continuum.

Training adaptations are known to be specific to the type of exercise performed. On the strength end of the exercise intensity continuum, the Nordic Combined athletes have traditionally focused on explosive strength training or power training of the lower extremity muscle (Pääsuke et al. 2001). The focus on power training is possibly due to the low impact on muscle hypertrophy and large effect on rate of force development and power production. During the take-off movement in the ski jump, athletes have approximately 0.3 seconds to produce a high momentum, which is a prerequisite for a successful ski jump (Müller 2009). However, typical endurance training, comparable with Nordic combined athletes training for cross country skiing, has been associated with reduced vertical jump ability (Costill 1967) and reduced or unchanged muscle strength (Costill 1967; Fitts et al. 1989; Kraemer et al. 1995; McCarthy et al. 2002; Widrick et al. 1996). Consequently, the main challenge for the Nordic Combined athletes is to optimize performance in both ski jumping and cross-country skiing. There is probably no universal answer to this question and individualization is compulsory.

Interestingly, work economy and/or endurance performance have been reported to improve in cycling, running, and double-poling after a period with heavy strength training (e.g. Hoff et al. 2002; Millet et al. 2002; Rønnestad et al. 2010a; 2011; Støren et al. 2008; Østerås et al. 2002). Importantly, no negative effects on aerobic capacity, measured as VO_{2max}, were observed in these studies. Furthermore, 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 (Mahood et al. 2001; Nesser et al. 2004; Terzis et al. 2006). Therefore, adding heavy strength training (especially on important upper body muscles) to the normal training regime in Nordic Combined athletes may have a positive effect on the cross country skiing part of their competition.

Another potential advantage of including heavy strength training in Nordic Combined athletes training regime is an improvement in vertical jump performance (e.g. Adams et al. 1992; Bauer et al. 1990). Consequently, heavy strength training of leg extensors may be advantageous for the ski jump performance. On the other hand; heavy strength training may increase muscle mass and body mass, and an increased body mass may potentially reduce some aspects endurance performance as well as ski jump performance (Knechtle et al. 2009; Müller 2009). However, combining large volumes of endurance training with heavy strength training seems to reduce the hypertrophic response to strength training (e.g. Aagaard et al. 2011; Kraemer et al. 1995; Losnegaard et al. 2011; Rønnestad et al. 2011b). It is therefore of interest to further investigate the effect of combining heavy strength training with large volumes of endurance training on muscle thickness and muscle strength and how it affects vertical jump performance, body mass, and endurance performance in Nordic Combined athletes.

The primary aim of the present study was thus to investigate the hypothesis that 12 weeks of heavy strength training, combined with the normal Nordic Combined training (endurance and power training), would positively affect vertical jump performance and skate-rollerskiing performance. We hypothesized that improved ski skating performance would be associated with improved work economy. Furthermore, it was hypothesized that improved jump performance would be associated with increased muscle thickness and muscle strength.

Methods

Participants

Seventeen well-trained Norwegian male Nordic Combined athletes completed the study. They were competing at national level (n=11) or international level (n=6). None of the athletes had performed heavy strength training during the last five months (during the competition season and the transition period just prior to the beginning of the intervention). During the preparatory period to the last competition season (6 to 10 months before the present intervention), 4 athletes in STR and 5 athletes in CON performed heavy strength training, while the rest of the participants in the two groups had no experience with heavy strength training. However, all participants had performed power training at regular basis during the year preceding the intervention. All athletes signed an informed consent form prior to participation. Three of the athletes were 17 years old and we had their parents' consent to participate in the study. The study was approved by the Regional Ethics Committee of Southern Norway and performed according to the Declaration of Helsinki.

Experimental design

The aim of the present study was to investigate the hypothesis that 12 weeks of heavy strength training combined with the normal Nordic Combined training would positively affect muscle strength, vertical jump performance, endurance performance, and work economy during skate-rollerskiing. To do this, Nordic Combined athletes were included in a group performing heavy strength training in addition to normal Nordic Combined training (STR; n=8, age 19±2 years, height 180±4 cm, body mass 69±4 kg), while Nordic Combined athletes performing only normal Nordic Combined training constituted a control group (CON; n=9, age 20±3 years, height 179±4 cm, body mass 68±3 kg). During the intervention period there was no statistical significant difference between the two groups in total training volume or number of ski jumps. The athletes could choose which group to attend. The reason why it was not possible to do this as a randomized trial was that the Nordic Combined athletes did not accept to be randomly allocated to extensive participating in 3 months of strength training or control testing. The tests were conducted at the start (pre-intervention) and at the conclusion (post-intervention) of a 12-week intervention. The number of athletes competing at an international level was the same in both STR and CON group. The intervention started at the same time as the start of the preparatory period. The pre-tests were thus preceded by a transition period of ~ 3-4 weeks with low training volume.

Training

The heavy strength training was performed twice a week. Adherence to the strength program was high, with STR athletes completing 84±4% of the prescribed strength training sessions. The goal of the strength training program was to improve vertical jump performance and skate-roller skiing performance. The rationale of the selected strategies was that it has been observed that improvement in vertical jump height theoretically results in an increased ski jump length (Hoff et al. 2001), and that a strong relationship between upper-body power and skating rollerski performance has been observed (Gaskill et al. 1999; Mahood et al. 2001). The two upper-body exercises targeted specific muscles used in cross-country skiing. The upper-body exercises utilized a handlebar specifically designed to imitate the grip on poles in cross country skiing (Losnegard et al. 2011). Free weights were used during the deep squat exercise. Based on the assumption that it is the intended rather than actual velocity that determines the velocity-specific training response (Behm and Sale 1993), the heavy strength training was conducted with focus on maximal mobilization in the concentric phase (lasting around 1 s), while the eccentric, and non-performance specific phase, was performed more slowly (lasting around 2-3 s).

At the start of each strength training session, athletes performed a ~10-min warm-up at self-selected intensity on a cycle ergometer, followed by 2-3 warm-up sets of squat with gradually increasing load. For the other exercises, one warm-up set per exercise (3-5 repetitions, 70-80% of 1RM) was performed before the maximal sets. The strength exercises were performed in the same order at each training session: deep squat, seated pull-down, and standing double-poling. During the intervention period, the number of sets in each exercise was between 3 and 5, and the load was between 3RM and 10RM (Table 1). Standing double-poling was performed with 10RM load throughout the intervention period because it was difficult to perform this exercise with correct technique with higher loads. The athletes were encouraged to increase their RM loads continually throughout the intervention period and they were allowed assistance on the last repetition. Rest between sets was 2-3 minutes. All athletes were supervised by an investigator at all workouts during the first two weeks and thereafter at least once every second week throughout the intervention period.

(Insert Table 1 approximately here)

The normal Nordic Combine training was managed by the athletes themselves and their coach. Athletes and coaches recorded each training session throughout the 12 weeks using a training log that was sent by e-mail to the project coordinator. Endurance training volume and intensity were calculated on the basis of recordings from heart rate (HR) monitors (Polar, Kempele, Finland). There were no differences between the two groups with regard to total volume of endurance training or distribution of endurance training within different heart rate intensity zones (Table 2). Although not statistical significant, the STR group had a slightly lower training duration with regard to power training and core training as compared to the CON group (1.2±0.1 and 1.4±0.2 hrs. vs. 2.0±0.4 and 1.7±0.3 hrs., respectively; Table 2). The reason for this was that some of the normal power training was replaced by heavy strength training in the STR group. There was no difference between STR and CON in mean weekly endurance training duration (6.5±0.5 hrs. vs 7.2±0.3 hrs., respectively; Table 2). Therefore, total weekly training duration (including heavy strength training) was not different between groups (12.0±0.6 hrs. in STR and 12.0±0.6 hrs. in CON; Table 2). In addition, the mean weekly number of ski jumps was similar in the two groups (Table 2).

(Insert Table 2 approximately here)

Testing

All athletes completed one familiarization session in the strength tests, squat jump (SJ), and on the rollerski treadmill in advance of the pre-tests. All athletes were familiar with outdoor rollerskiing. Two test days were performed before and after the intervention period: On the first test day a 7.5 km outdoor rollerski time trial was performed. The second test day was performed one week later and included the following measurements in the following order:

Ultrasound imaging to measure muscle thickness, fascicle angle and fascicle length, SJ, work economy in rollerskiing on treadmill, VO_{2max} and 1RM tests. All test procedures, including the order of tests and time of day were identical at pre- and post-test. To stimuli optimal arousal levels, the athletes were given verbal encouragement throughout all tests that required maximal effort. Athletes were instructed to prepare themselves as they would do for a real competition, and ensure proper hydration status and rest.

7.5 km rollerski time-trial

The 7.5 km skate-rollerskiing time trial was performed outdoor by performing 3 circuits in a 2.5 km long rollerski track with freely-chosen skate technique (the longest and steepest hill being 370 meters with an average inclination of 3°). The same physical pair of rollerskis was used by each athlete at pre-test and post-test. The rollerskis were new at pre-test and stored in a dark, dry room during the intervention period. Swenor skating skis (Model 65-000 SKATE. Sport Import AS, Sarpsborg, Norway) with wheel type 2 were used. Athletes were instructed to prepare themselves as they would do for a real competition and performed a 30 min individual warm-up on rollerskis. Athletes started individually at 30-sec intervals. The track was dry on both pre- and posttest and the temperature was 18-22°C for both pretest and posttest.

Ultrasound imaging

In vivo muscle architecture was examined using two dimensional (2-D) ultrasonography (HD11 XE ultrasound system, Phillips Medical Systems, Veenpluis, Netherland) with a 5.5 cm linear array probe (7.5 MHz). This type of 2-D ultrasound has, as in the present study, commonly been used to measure muscle architecture, muscle thickness, and muscle length (e.g. Aagaard et al. 2001; Blazevich et al. 2003; Kanehisa et al. 2003). These measurements are made possible by echoes reflected from the superficial and deep aponeuroses and the interspaces among the fascicles which clearly delineate these structures and allows architectural measurements to be made. Measurement of muscle thickness by 2-D ultrasonography has been validated against magnetic resonance imaging scans in various human muscles and found to be <2 mm difference (Dupont et al. 2001; Juul-Kristensen et al. 2000). Furthermore, measures of fascicle angle and fascicle length by 2-D ultrasonography have been shown to be similar to those measured directly in cadavers (Chleboun et al. 2001; Kawakami et al. 1993; Narici et al. 1996). When the sonographs were performed, the athletes lay supine with no flexion in the knee joint with legs supported and muscles relaxed. A transmission gel (DANE – GEL® E2, Rohde Produits, Holte, Danmark) was applied to the probe to aid acoustic contact and reducing the needed pressure from the probe against the muscle. Three sonographic scans were performed on both right and left leg with the probe orientated parallel to the muscle length and perpendicular to the skin. The probe was placed longitudinal at the middle of femur (midway between the greater trochanter and knee joint space). On the sonographs of m. vastus lateralis thickness was measured at proximal, middle and distal sites on the images. Muscle thickness was measured as the distances between superficial and deep aponeuroses in all three sonographs in both legs and the mean value was used in statistical analyses (CV ≤ 3%). Fascicle angle was measured in all three sonographs and the mean value in each leg was used in the statistical analyses (CV ≤ 5%). At all sites tested, the fascicles were too long to be measured from origin to insertion. Hence, fascicle length was estimated using the measurements of muscle thickness and fascicle angle (fascicle length = muscle thickness/sin(fascicle angle); Alegre et al. 2006).

Squat jump height

On the first test day, the athletes performed a 10-min warm-up on a cycle ergometer. SJ performance was tested on a force plate (SG-9, Advanced Mechanical Technologies, Newton, Mass., USA, sampling frequency of 1 KHz). No stretching was allowed prior to or during the jump test. The hands were kept on the hips throughout the jump, knees were flexed to 90º, and the athletes were instructed to execute a maximal vertical jump without plantar flexion of the ankle joint. To assure similar knee angle in all attempts, the athlete's SJ depth was individually controlled by a marker. Thus the athlete had to reach his individual depth (touch the marker with the buttocks) in all jumps. No downward movement was allowed prior to the maximal vertical jump, and the force curves were inspected to verify this. Vertical jump height was determined as the centre of mass displacement calculated from force development and measured body mass. Each participant performed five attempts, with 1 minute rest between each jump. The athletes were blinded to the results. The mean of the two best jumps from each participant was used in data analysis (CV<3%).

Rollerskiing on treadmill

Work economy and VO_{2max} tests during rollerskiing, were performed on a treadmill with belt dimensions of 3 x 4.5 m (Rodby, Sodertalje, Sweden). 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 ($\mu = 0.014$) in the wheels. Swix CT1 poles (Swix, Lillehammer, Norway) with a tip customized for treadmill rollerskiing were used. The V1 skating technique (“paddling”, “gear two”) with optional strong side, was used during the submaximal rollerskiing, while it was optional skating technique during the VO_{2max} test. We have recently shown that there is no difference between the V1 and V2 skating techniques in moderate to step inclinations with regard to VO_{2max} (Losnegard et al. 2010). After a 15-min warm up (60-70% of HR_{max}) on the treadmill the athletes completed 2 x 5-min bouts with a 2-min break between each effort. The speed on the treadmill at submaximal tests was set to 3 $m \cdot s^{-1}$, with inclines of 4 and 5°. Work economy in the present study was defined as the average VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$) between 2.5 and 4.5 minutes at each incline (CV<2%). VO_2 was measured by an automatic system (Oxycon Pro, Jaeger Instrument, Hoechberg, Germany) with 30 s epochs, evaluated by Foss and Hallén (2005). Heart rate (HR) was measured between 2.5-4.5 minutes with Polar S610i™ (Polar electro OY, Kempele, Finland) and blood lactate concentration was measured in unhaemolysed blood, from capillary fingertip samples. Blood was taken in a heparinised capillary tube, from which 25 µl was injected with a pipette into the mixing chamber of the lactate analyser (YSI 1500 Sport, Yellow Spring Instruments, OH, USA). The lactate analyzer and Oxycon Pro Jaeger Instrument were calibrated according to the instruction manual and described in detail by Losnegard et al. (2011). Rate of perceived exertion (RPE) was recorded 4 min and 50 s into each period, using Borg’s 6-20 scale (Borg 1982). Ten minutes after the last submaximal effort, the athletes performed a VO_{2max}. Athletes started at 5° incline and 3 $m \cdot s^{-1}$. With constant speed, incline was subsequently increased by one degree every minute until 8°. Thereafter speed was increased by 0.25 $m \cdot s^{-1}$ every minute. 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 one minute was taken as VO_{2max}. Blood plasma lactate concentration and RPE was measured immediately after termination of the VO_{2max} test. Thereafter, 5 minutes of cooldown on the treadmill was preceding 15 minutes of rest before the assessment of 1RM strength.

1 RM strength tests

The 1RM tests for deep squat and seated pull-down were performed 20 minutes after the rollerski testing on treadmill. In both exercises, the athletes performed 3 sets of exercise-specific warm-up with gradually increasing load (10 repetitions at 40%, 6 repetitions at 60%, and 3 repetitions at 80% of 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 athlete failed to lift the load after 2–3 consecutive attempts. The rest period between each attempt was 3-4 minutes. The order of tests was identical at both pretest and posttest. All 1RM testing was supervised by the same investigator, at the same time of day and conducted on the same equipment with identical equipment positioning for each athlete. A powerlifting belt was used around the waist for support and safety during the squat exercise. The athletes were given verbal encouragement throughout the testing. During the 1RM tests in deep squat the International Powerlifting Federation standard was used. For the seated pull-down, a Tecnogym Radiant (Tecnogym, Gambettola, Italy) apparatus was used (for further details, see Losnegard et al. 2011). The movement started with the handlebar positioned at the same height as the forehead. The athletes 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 hands parallel.

Statistics

All results are reported as means and standard error (SE) unless otherwise stated. All data showed a normal distribution (Gaussian distribution), and consequently parametric tests were applied. Mean effect size (ES) was calculated as Cohen’s d to compare the practical significance of the performance improvements among the two groups (0.2, 0.5, and 0.8 equal small, moderate and large, respectively). Paired t-test was used for detecting significant changes from pre-test to post-test within groups and unpaired t-test was used to detect significant differences between groups in relative changes. Two-way repeated measures ANOVA (time of intervention period and inclination as factors) with Bonferroni post hoc tests were performed to evaluate differences within groups (post- vs. pre-values) in responses during the submaximal rollerskiing. In addition, two-way repeated measures ANOVA (group and inclination as factors) with Bonferroni post hoc tests were performed for evaluation of differences in relative changes (post- vs. pre-values) between groups. ANOVA analyses were performed in GraphPad Prism 5 (GraphPad Software Inc., CA, USA). Student's t-tests and Pearson's product moment correlation analysis were performed in Excel 2010 (Microsoft Corporation, Redmond, WA, USA). A p-value ≤ 0.05 was considered statistically significant.

Results

Comparison of groups at baseline

There were no significant differences between STR and CON at baseline with respect to the 1RM tests, SJ height, muscle thickness of *m. vastus lateralis*, fascicle angle and fascicle length in *m. vastus lateralis*, body mass, VO_{2max}, work economy or performance during rollerskiing.

Training load, strength, and jump performance

The STR group increased their average weekly strength training volume (kg x reps x sets) from the first training week to the last training week (from 1400±57 kg to 1720±103 kg, $p<0.01$). The STR group increased their 1RM in deep squat and seated pull-down by 12±2% and 23±5%, respectively ($p<0.01$; Figure 1), while no changes occurred in CON. The relative increase in 1RM deep squat and seated pull-down was larger in STR than in CON ($p<0.01$; Figure 1, ES=2.9 and 1.5, respectively). STR increased their SJ performance by 8.8±1.7% ($p<0.01$; Figure 2), while no statistical significant change occurred in CON (Figure 2). The relative change in SJ performance was larger in STR than in CON ($p<0.05$, ES=1.1).

(Insert Figure 1 approximately here)

(Insert Figure 2 approximately here)

Body mass, muscle thickness, fascicle angle and –length in m. vastus lateralis

There was no change in body mass from pre- to post-intervention in any of the two intervention groups. The muscle thickness of m. vastus lateralis increased by 7.4±2.7% ($p<0.05$; Figure 3) in STR, while a tendency towards reduced muscle thickness was observed in CON (-3.0±1.4%, $p=0.08$; Figure 3). The relative increase in muscle thickness was larger in STR than in CON ($p<0.01$; Figure 3, ES=1.7). There was no statistical significant changes in fascicle angle or fascicle length in any of the groups, but there was a tendency towards a reduction in CON($p=0.08$; Table 3).

(Insert Figure 3 approximately here)

(Insert Table 3 approximately here)

Maximal oxygen uptake during skate-rollerskiing

No change in VO_{2max} was observed in either STR or CON (pre values were 66.4±1.8 $ml \cdot kg^{-1} \cdot min^{-1}$ and 66.0±1.6 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively and post values were 66.2±1.6 $ml \cdot kg^{-1} \cdot min^{-1}$ and 66.1±1.5 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively).

Submaximal treadmill rollerskiing

ANOVA analysis showed that in the submaximal rollerskiing test, work economy, determined as body-mass adjusted oxygen consumption, was improved by 3.8±1.5% in STR at an inclination of 5° ($p<0.05$; Table 4), while it remained unchanged at 4°. There were no statistical significant changes in work economy in CON (Table 4). HR in STR was lowered by 4.4±1.5% and 3.5±1.1% at an inclination of 4° and 5°, respectively ($p<0.05$; Table 4), while no statistical significant changes in submaximal HR was observed in CON (Table 4). In addition, RPE for STR was reduced at an inclination of 5° ($p<0.05$; Table 4), but not at 4°, while no changes in RPE was observed in CON (Table 4). The blood lactate concentration during the submaximal rollerskiing remained unchanged during the intervention period for

STR and CON at both 4° and 5° inclination (Table 4). A comparison between STR and CON of the relative changes from pre- to post-intervention showed no significant difference between groups in parameters measured during the submaximal rollerskiing tests.

(Insert Table 4 approximately here)

7.5 km rollerski time-trial performance

7.5 km rollerski time-trial performance did not change significantly from before to after the intervention period in either STR (from 20.39±0.94 min to 19.78±0.38 min, respectively) or CON (from 19.77±0.50 min to 19.54±0.42 min, respectively).

Discussion

Twelve weeks of supplemental heavy strength training in Nordic Combined athletes increased muscle thickness and muscle strength, without changing total body mass. Of practical importance, supplemental heavy strength training improved vertical jump performance and had no negative impact on the development of the endurance capacity. No statistical significant changes in these measurements were found in the CON group.

1RM, muscle thickness and muscle architecture

During the 12 weeks intervention STR increased strength in deep squat by ~12%. This increase is similar to what Losnegard et al. (2011) observed in cross-country skiers after a similar strength training intervention. However, the increase in leg strength is somewhat smaller than the 25-27% that has been reported in other endurance athletes (Hickson et al. 1988; Millet et al. 2002; Rønnestad et al. 2011a). Interestingly, in the latter studies a larger strength training volume including multiple leg exercises was performed. In the present study, as well as in the study of Losnegard et al. (2011), only the squat exercise was performed for leg muscles. It has been shown that large volumes of endurance training reduce strength training adaptations (e.g. Hickson 1980; Kraemer et al. 1995; Rønnestad et al. 2011). It may therefore be hypothesized that the rather small improvement in 1RM deep squat in the present study was due to the combination of a small strength training volume and a large endurance training volume on leg muscles. Indeed, during the first months of strength training it seems like development of lower-body muscle strength is more dependent on strength training volume than upper-body muscles (e.g. Rønnestad et al. 2007). Furthermore, the increase in upper-body strength was almost twice of the increase in lower-body strength, and there was a tendency towards larger strength improvement in the upper-body compared to the lower-body (p=0.11). The increase of ~23% in upper-body strength was within the expected range of improvement (Kraemer et al. 2002). This may partly be explained by a larger strength training volume on the upper-body muscles and a lower endurance training volume in these muscles. A lower endurance training volume in the upper-body is explained by the use of running and cycling in the endurance training. A similar finding was presented almost two decades ago by Kraemer et al. (1995). They found that when lower-body strength training was added to running, the strength training adaptations was reduced, while the upper-body strength training adaptations was not altered when combined with running. The mean ES of the present 1RM improvements revealed a large practical relevant difference between the groups (ES > 0.8).

The Nordic Combine athletes are experienced with power/explosive strength training and it is known that this type of training have minor impact on muscle hypertrophy (e.g. Holm et al. 2008). It is therefore reasonable that these athletes achieve gains in muscle thickness in when they begin with heavy strength training. During the strength training period, the muscle thickness of m. vastus lateralis increased by ~7%, which is in line with previous findings in competitive team sports athletes after a training period with strength training (Blazevich et al. 2003), and slightly less than the ~12% increase in muscle thickness observed after heavy strength training in previous untrained subjects (Blazevich et al. 2007a; Cormie et al. 2010). These findings indicate an antagonistic effect of endurance training on muscle growth. This antagonistic effect of endurance training is also supported by observations of 0-5% increase in muscle cross-sectional area or lean body mass after 12-16 weeks of concurrent strength and endurance training in well-trained endurance athletes (Aagaard et al. 2011; Losnegard et al. 2011; Rønnestad et al. 2010a). The latter findings suggest an impaired hypertrophic response to the strength training as compared to the expected changes in normal active subjects (e.g. Wernbom et al. 2007). Impaired muscle hypertrophy with concurrent strength and endurance training seems to be explained by recent developments within molecular sports science. It has been shown that endurance exercise attenuates intracellular pathways important for myofibrillar protein synthesis (reviewed in Hawley 2009). Consequently, it seems that the acute intracellular signaling response to concurrent strength and endurance training, does not promote ideal activation of pathways responsible for muscle hypertrophy (Coffey et al. 2009). Despite a smaller increase muscle thickness than earlier observed in untrained subjects, the mean ES of the changed muscle thickness in the present study revealed a large effect of adding heavy strength training (ES > 0.8).

It must be emphasized, that despite the increase in muscle strength and muscle thickness in the strength trained muscles there was no change in total body mass. This is an important finding, because increased body mass may potentially reduce some aspects of endurance performance as well as ski jump performance. No increase in body mass is supported by the majority of studies investigating the effects of concurrent training on both muscle hypertrophy and strength (Aagaard et al. 2011; Losnegard et al. 2011; Rønnestad et al. 2010a), or strength alone in endurance athletes (Hoff et al. 2002; Millet et al. 2002; Støren et al. 2008; Østerås et al. 2002). The present study lasted only 12 weeks and it is difficult to speculate on any long-term consequences of this heavy strength training program. Therefore, the heavy strength training protocol used in this study may be regarded as a "peaking" protocol. Furthermore, it is important for the athletes to maintain the new level of strength and jump performance. It has recently been shown that endurance athletes are able to maintaining a new level of strength even with a quite low strength training volume (Rønnestad et al. 2010b).

We are not aware of any previous studies investigating fascicle angle and fascicle length in Nordic Combined athletes. The pre values of both fascicle length and -angle in *m. vastus lateralis* in the present study seem reasonable because they were in-between the values reported in 100-m sprinters and long distance runners (Abe et al. 2000). Given previous findings of a strong relationship between muscle thickness and fascicle angle (Blazevich et al. 2007a; Kawakami et al. 1993; 1995), it was somewhat unexpected to find no statistical significant change in fascicle angle in the STR group, despite increased muscle thickness. However, relative changes in muscle thickness and fascicle angle were significantly correlated (r=0.64, *p*<0.01) and it has also previously been found a non-linear relationship between muscle architectural variables (Alegre et al. 2009). In contrast to the present finding, strength training alone has been shown to increase fascicle angle after 14-16 weeks of strength training (Aagaard et al. 2001; Kawakami et al. 1995). However, during shorter periods of strength training the findings are equivocal (Blazevich et al. 2007a; 2007b; Seynnes et al. 2007). An increased fascicle angle may potentially allow a greater amount of contractile tissue to attach to the tendon and thereby increase muscle strength (Blazevich et al. 2007a). No significant increase in fascicle angle in m. vastus lateralis may thus contribute to explain the rather moderate increase in 1RM deep squat in the STR group.

Fascicle length impacts on the length range and speed of active force generation, and thus affect muscle power output. Fascicle length of *m. vastus lateralis* has been found to be highly predictive of 100-m sprint time in sprinters (Kumagai et al. 2000). It could therefore be suggested that increased fascicle length was a prerequisite for further improvement in a high-power demanding exercise, like a vertical jump in Nordic Combined athletes. On the contrary, and partly in agreement with the present findings, it has recently been observed that no muscle architectural parameters in *m. vastus lateralis* can predict jump performance (Earp et al. 2010). The latter points to the possibility to improve vertical jump ability without significant changes in fascicle length or fascicle angle, like in the present study. It has been observed that muscle loadings at high velocities are associated with fascicle length increases (Alegre et al. 2006; Blazevich et al. 2003). Moreover, fascicle length adaptations seem to occur rapidly and do not continue past the first few weeks of training (Blazevich et al. 2007a; Seynnes et al. 2007). It is therefore possible that the Nordic Combined athletes already had approached their potential for fascicle length adaptations during previous years of explosive power and jump training.

Squat jump

The finding of improved vertical jump performance in the STR group is in agreement with previous studies involving distance runners and soccer players adding strength training to their normal training (Rønnestad et al. 2008; Spurrs et al. 2003), but in contrast to other studies, in which no improvement in vertical jump performance was observed after adding strength training to a high volume of endurance training (Losnegard et al. 2011; Millet et al. 2002). Increased jumping ability is an expected adaptation when individuals with no prior experience of heavy strength training complete a period of strength training (e.g. Cormie et al. 2010). The mean ES of the SJ improvements in the present study revealed a large practical effect of the heavy strength training (ES > 0.8). Maximal strength of the leg extensors, measured as 1RM squat, and especially when expressed relative to body mass, clearly contributes to vertical jump performance (Carlock et al. 2004). In agreement with the latter, there was a correlation between relative changes in 1RM squat and relative changes in SJ performance in the present study ($r = 0.59$, $p<0.05$). Whether an athlete will improve vertical jump ability as a consequence of increased muscular strength seems to depend on how strong the athlete is in the beginning of the strength training intervention (Häkkinen and Komi 1985). The latter may contribute to explain the discrepancy in the literature. Since the athletes in the present study had not undertaken any heavy strength training during the previous 5 months, it seems likely that they had a rather low initial muscular strength.

Interestingly, in World-Cup ski jumpers, undergoing a similar strength training intervention as in the present study, a similar increase in 1RM deep squat and vertical jump ability was observed (~13% and ~6%, respectively; Hoff et al. 2001). It should, however, be noted that in the latter study, no control group was included, so the results should be interpreted carefully. Even though actual ski-jump performance was not measured in the present study, improving the vertical component in the same range of motion can theoretically increase the ski-jumping length. It has been suggested that an improvement of vertical jump height of 1 cm may result in an increased ski-jumping length of 1 to 1.5 m (Hoff et al. 2001). The latter indicated that the mean increase in vertical jump height of ~ 3 cm in the present study, may potentially increase the ski-jumping length by 3 to 4.5 m, which may be of great importance for the final result in a Nordic Combined competition. However, this extrapolation of the results must be carefully interpreted because ski-jump performance is extremely complex and affected by a numerous of factors besides vertical jump ability (Schwameder 2008).

Treadmill rollerskiing and rollerski time-trial performance

No difference between the STR group and CON group in the development of VO_{2max} is in accordance with the majority of similar studies on well-trained endurance athletes (e.g. Hoff et al. 2002; Millet et al. 2002; Rønnestad et al. 2010a; Støren et al. 2008; Østerås et al. 2002).

It is important to note that the supplementation of heavy strength training twice a week during the 12-week intervention period did not negatively affect the development of VO_{2max}.

The STR group improved work economy at submaximal treadmill rollerskiing at an inclination of 5° with a concomitant reduction in HR and RPE, while there was a trend towards improvement in work economy in CON. However, there was no significant difference between the groups in relative change. This is underlined by the ES which showed no effect of the heavy strength training on changes in work economy (ES=0.1). Although, no difference between the groups in the present study, the finding of improved work economy in the STR group is in accordance with previous studies in cross-country skiers on a double-poling ergometer (Hoff et al. 2002; Østerås et al. 2002). On the other hand, in a recently performed study with a similar strength training program as in the present study, no change in submaximal treadmill rollerskiing work economy was found in cross-country skiers (Losnegard et al. 2011). A possible explanation to some of this discrepancy may be related to the fact that cross-country skiers are specialized in cross-country skiing only, while the Nordic Combined athletes have to focus on ski-jumping performance in addition to cross-country skiing. It is therefore likely that the cross-country skiers in the study of Losnegard et al. (2011) had optimized their skating technique in way that improving their muscular strength had no further effect on work economy. However, it has been suggested that cross-country skiers with initial low muscle strength are more likely to increase performance than initial stronger skiers when supplementing their normal training routines with strength training (Losnegard et al. 2011). The upper-body 1RM test in the present study was identical with the one performed in the study of Losnegard et al. (2011) and when the mean baseline values were compared, we do see that the Nordic Combined athletes were weaker than the cross-country skiers of the same gender (~34 kg vs. ~44 kg, respectively). The observation of improved work economy at an inclination of 5° and not at 4°, when the demand of muscular strength to perform the optimal technique is less, may suggest a positive effect of strength training in skiers with initial low muscle strength.

The improved work economy and tendency towards improved economy should in theory result in improved time trial performance. However, none of the groups improved their time trial performance. Importantly, improved work economy in STR was only observed at the highest inclination, and therefore it is likely that this improvement was not detected in the rollerski track which was rather flat (the longest and steepest hill being approximately 370 meters with an average inclination of approximately 3°). It is therefore likely that the rollerski track was too flat to detect any performance increase as a result of improved muscular strength. On the other hand, a strong relationship between upper-body power and skating rollerski performance has been observed (Gaskill et al. 1999; Mahood et al. 2001). Unfortunately, upper-body power was not measured in the present study, but there were no relationship between individual changes in upper-body strength and time trial performance. Finally, during outdoor time trial tests, confounding elements like weather, surface and unaccustomed rollerskis may give rise to larger variations in performance. Consequently, it may be harder to find intervention effects. That being said, the track was dry on both pre- and posttest and the temperature was between 18-22°C for both pretest and posttest.

In conclusion, 12 weeks of supplementing normal Nordic Combined training with heavy strength training twice a week increased muscle thickness of m. vastus lateralis as well as upper- and lower-body strength in well-trained Nordic Combined athletes without increasing total body mass or compromising the development of VO_{2max}. Of even larger practical importance to the athletes, the strength training also resulted in improved vertical jump performance relevant for ski-jump performance. This improvement was larger than in the CON group. There were no statistical significant changes in any of the performed measurements in the CON group. Altogether; supplementing heavy strength training seems to improve determinants of performance in Nordic Combined by improving the athletes' strength and vertical jump ability.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Figures

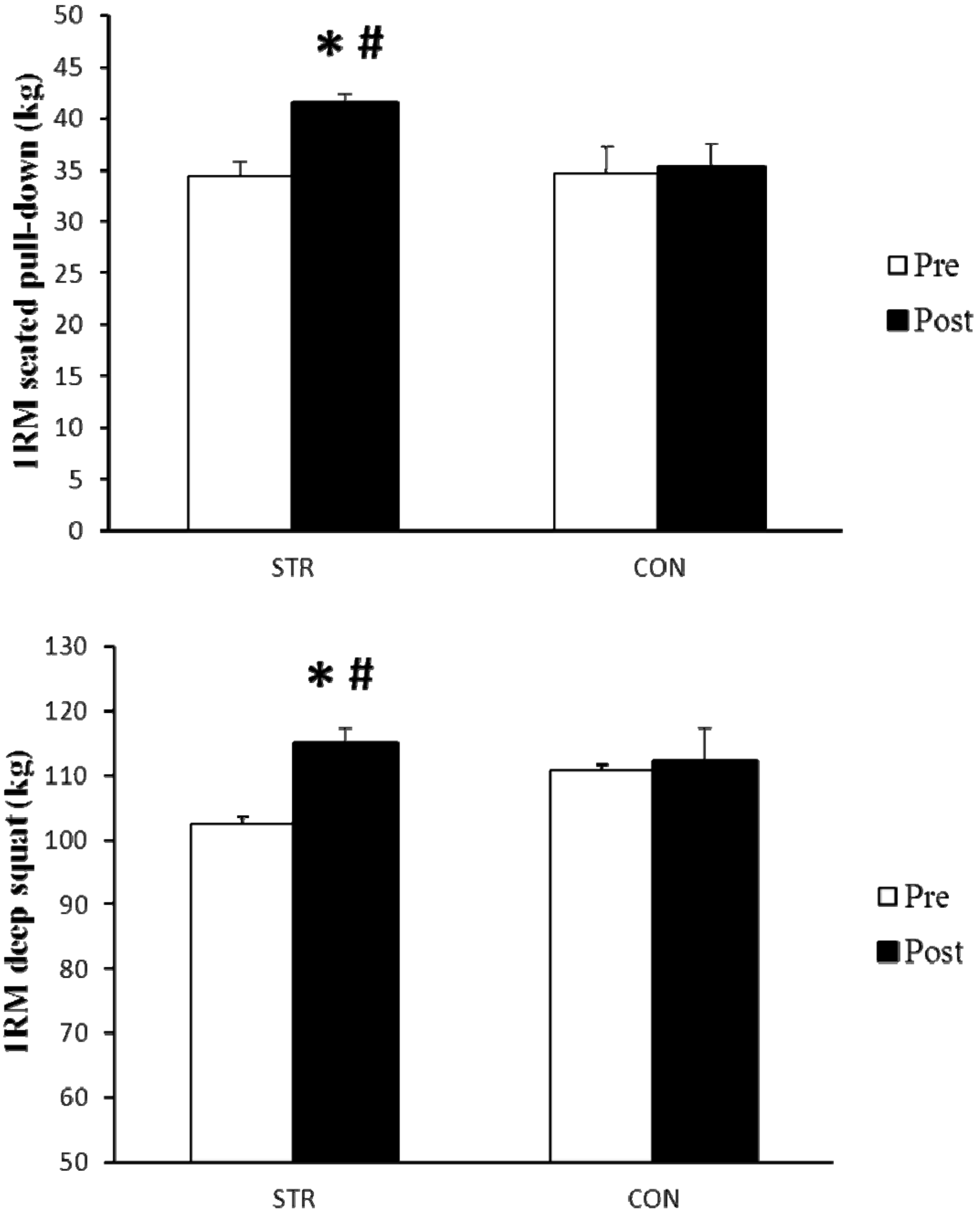

Fig. 1 1RM load in seated pull-down and in deep squat (upper and lower panel, respectively) before (Pre) and after the 12 week intervention period (post). STR = Strength training in addition to usual Nordic Combined training, CON = Usual Nordic Combined training without heavy strength training. *Larger than at Pre (p<0.05). $^{\#}$The relative change from Pre is larger than in CON (p<0.05)

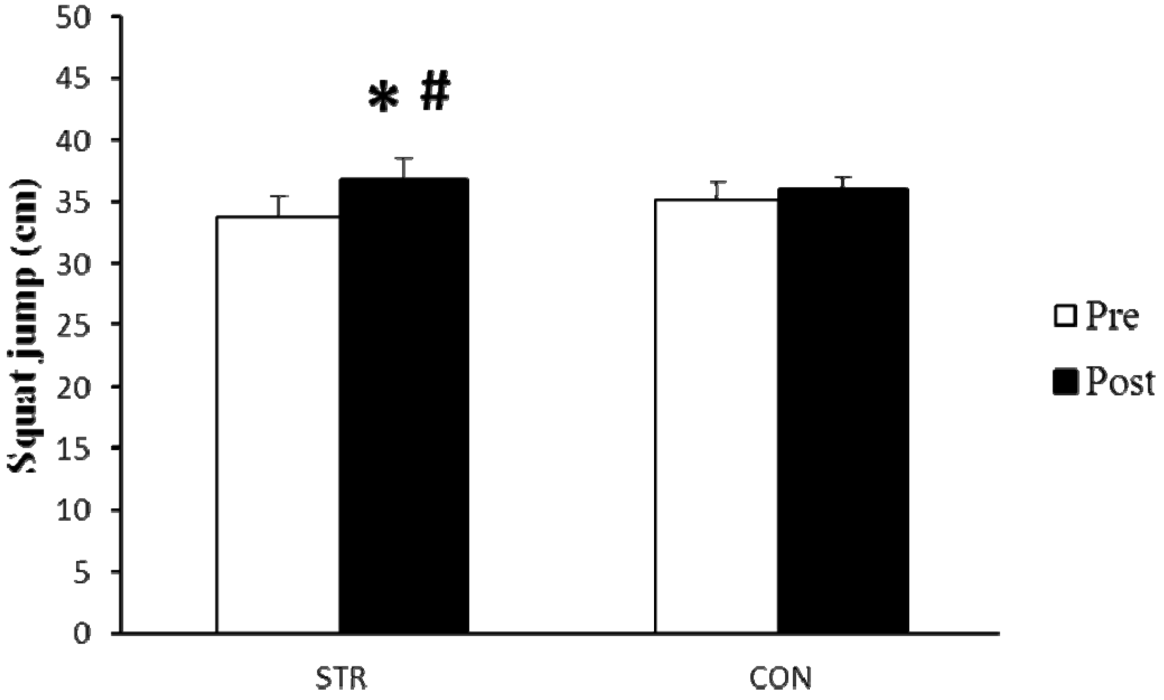

Fig. 2 Squat jump height before (Pre) and after the 12 week intervention period (post). STR = Strength training in addition to usual Nordic Combined training, CON = Usual Nordic Combined training without heavy strength training. *Larger than at Pre (*p*<0.05). $^{\#}$The relative change from Pre is larger than in CON (*p*<0.05)

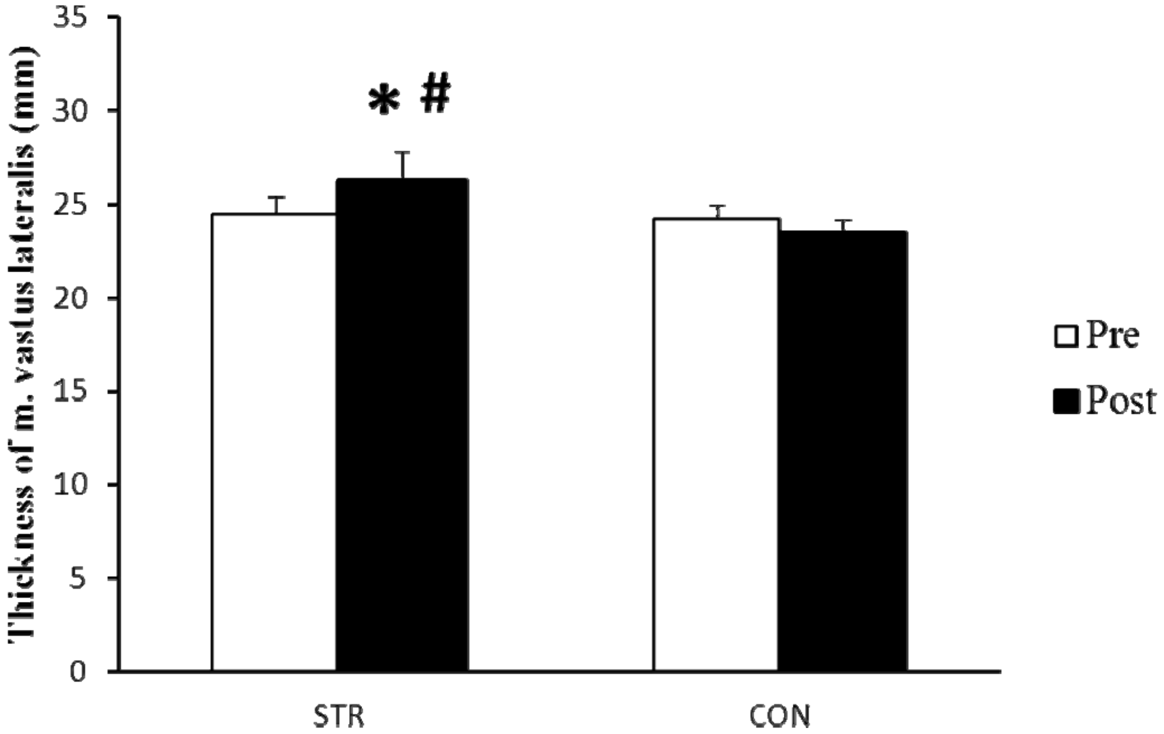

Fig. 3 Thickness of m. vastus lateralis before (Pre) and after the 12 week intervention period (post). STR = Strength training in addition to usual Nordic Combined training, CON = Usual Nordic Combined training without heavy strength training. *Larger than at Pre (*p*<0.05). $^{\#}$The relative change from Pre is larger than in CON (*p*<0.05)

Table 1 Strength training program for the Nordic combine athletes who performed heavy strength training.

	Week 1-6		Week 7-12	
	1. bout	2. bout	1. bout	2. bout
Deep squat	3x8RM	5x4RM	4x5RM	5x3RM
Seated pull-down	3x10RM	3x6RM	3x8RM	3x5RM
Standing double-poling	3x10RM	3x10RM	3x10RM	3x10RM

Table 2 Weekly duration (in hours) of the training distributed into different training activities and weekly number of ski jumps performed during the 12-week intervention period in the group which added heavy strength training to their Nordic Combine training (STR) and the group which performed usual Nordic Combine training only (CON)

	STR	CON
Endurance training:		
60%-72% of HR_{max}	4.9 ± 0.6	5.5 ± 0.3
73%-82% of HR_{max}	0.7 ± 0.2	0.7 ± 0.3
83%-87% of HR_{max}	0.5 ± 0.1	0.5 ± 0.1
88%-92% of HR_{max}	0.2 ± 0.1	0.2 ± 0.1
93%-100% of HR_{max}	0.2 ± 0.1	0.2 ± 0.1
Other training:		
Core training	1.4 ± 0.2	1.7 ± 0.3
Flexibility training	1.4 ± 0.2	1.1 ± 0.1
Power training	1.2 ± 0.1	2.0 ± 0.4
Heavy strength training	1.4 ± 0.2	
Ski jumps (number)	13.1 ± 1.0	12.5 ± 1.0
Total training duration	12.0 ± 0.6	12.0 ± 0.6

Values are mean±SE. HR_{max}: maximal heart rate

Table 3 Fascicle angle and fascicle length from m. vastus lateralis before and after the 12-week intervention period in which one group of Nordic combined athletes performed heavy strength training and their normal training (STR), while the other group simply continued their normal training (CON).

	STR (n=11)			CON (n=9)		
	Pre	Post	Change (%)	Pre	Post	Change (%)
Fascicle angle (°)	22.1 ± 1.0	22.8 ± 1.1	3.9 ± 4.1	21.1 ± 1.2	19.5 ± 1.2$^{\#}$	-7.3 ± 3.2
Fascicle length (cm)	6.6 ± 0.4	6.8 ± 0.3	3.9 ± 2.6	6.9 ± 0.5	7.2 ± 0.5	4.3 ± 4.4

Values are mean±SE. $^{\#}$ Tendency to reduction from pre and tendency to be lower than STR at post-test (*p*=0.08)

Table 4 Oxygen consumption (VO_2), heart rate (HR), blood lactate concentration ($[La^-]$), and rate of perceived exertion (RPE) during skate rollerskiing at 4° and 5° inclines with a constant speed of 3 $m·s^{-1}$ on the treadmill. STR = Strength training in addition to usual Nordic Combined training, CON = Usual Nordic Combined training without heavy strength training.

	STR (n=8)				**CON (n=9)**			
	4°		5°		4°		5°	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
VO_2 ($ml·kg^{-1}·min^{-1}$)	47.3±1.0	45.5±0.7	54.4±1.1	52.3±0.8*	46.6±1.4	45.4±0.8	54.1±1.4	52.4±1.0
HR ($beats·min^{-1}$)	172±4	164±4*	184±4	178±4*	168±4	165±4	180±4	177±4
$[La^-]$ ($mmol·l^{-1}$)	2.1±0.1	1.9±0.1	3.6±0.3	3.3±0.3	2.5±0.2	2.3±0.2	3.8±0.2	3.4±0.3
RPE	11.8±0.8	10.9±0.6	14.9±0.6	13.6±0.5*	11.9±0.7	11.8±0.6	15.1±0.6	14.6±0.5

Values are mean±SE. $^{\#}$ Lower than Pre values (*p*<0.05)
STR= strength training group; CON= control group