Title: **Strength training improves double poling performance after prolonged submaximal exercise in cross-country skiers**

**Running head:** Strength training & double poling performance

**Keywords:** cross-country skiing, concurrent training, endurance performance, maximal strength training, vibration training.

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**Abstract**
The purpose of this study was to investigate the effects of adding strength training with or without vibration to cross-country (XC) skiers’ endurance training on double poling (DP) performance, physiological and kinematic adaptations.

Twenty-one well-trained male XC skiers combined endurance- and upper-body strength-training three times per week, either with (n=11) or without (n=10) superimposed vibrations for 8 weeks, whereas eight skiers performed endurance training only (CON). Testing included 1RM in upper-body exercises, work economy, neural activation, oxygen saturation in muscle and DP kinematics during a prolonged submaximal DP roller ski test which was directly followed by a time to exhaustion (TTE) test. TTE was also performed in rested state and the difference between the two TTE-tests (TTEdiff) determined the ability to maintain DP performance after prolonged exercise.

Vibration induced no additional effect on strength or endurance gains. Therefore, the two strength-training groups were pooled (STR, n=21). 1RM in STR increased more than in CON (*P* < 0.05), and there were no differences in changes between STR and CON in any measurements during prolonged submaximal DP. STR improved TTE following prolonged DP (20±16%, *P* < 0.001) and revealed a moderate effect size compared to CON (ES = 0.80; *P* = 0.07). Furthermore, STR improved TTEdiff more than CON (*P* = 0.049).

In conclusion, STR superiorly improved 1RM strength, DP performance following prolonged submaximal DP and TTEdiff, indicating a specific effect of improved strength on the ability to maintain performance after long-lasting exercise.

**Introduction**

Cross-country (XC) skiing involves whole-body endurance exercise, with the work shared to various degrees between the upper- and lower-body in the different techniques employed. The greatest demands of upper-body power is found in double poling (DP), a technique of increased importance in XC-skiing due to improved equipment, better prepared tracks and thereby higher racing speeds [1-5]. In previous studies, DP performance has shown moderate to nearly perfect correlations with upper-body strength and power [6-9]. Moreover, increased muscle strength has changed cycle length at a given cycle rate in DP [9], increased muscle oxygen saturation during a time to exhaustion test [10], as well as reduced muscle activation during prolonged submaximal exercise [11]. Furthermore, several studies have investigated the effects of adding upper-body strength training (STR) to the ongoing endurance training in XC-skiers with different results. While STR improved performance and work economy in a DP ergometer [12-14], other studies report similar improvements in roller ski time trial performance between STR and endurance training only [7, 15, 16].

The importance of DP performance is further exaggerated in long-distance XC races, which are often performed as mass starts with submaximal DP for 2-4 hours followed by an all-out performance at the end of the race. This is the first study to examine the effects of STR on DP performance after prolonged submaximal DP in XC-skiers. It has been observed improved work economy during the last part of 3-hr prolonged cycling among both male and female cyclists that added STR to their usual training routine [17, 18]. The superior work economy likely explained the improved 5-min all-out cycling performance after the prolonged exercise with added STR-training both in men [18] and women [17]. Furthermore, some studies indicate that adding vibration to a strength exercise can acutely increase maximal force and power output [19-21]. The larger exercise stimulus induced with vibrations can in theory facilitate greater strength training adaptations than similar training without vibration [22]. To date none of these aspects has yet been examined in XC-skiing or other types of upper-body dominant modes.

The main purpose of the present study was to investigate the effects of 8 weeks of adding STR with or without vibration to regular endurance training on strength adaptations and DP performance with or without prolonged submaximal DP. The secondary purpose was to investigate possible strength training effects on work economy, muscle saturation, electromyography (EMG) activity and movement kinematics during prolonged DP. Our main hypothesis was that STR would induce larger effects on strength gains and DP performance than endurance training only, and in particular when DP performance followed prolonged submaximal exercise. Additionally, we expected that adding vibration to the strength exercises would further increase maximal strength and endurance gains compared to traditional strength training.

**Method**

Participants
Twenty-nine well-trained male XC-skiers volunteered for the study (Table 1), which was approved by the Local Ethics Committee at Lillehammer University College. Written informed consent was obtained from all participants prior to inclusion, and the study was carried out in accordance with the Declaration of Helsinki. None of the skiers had performed any systematic heavy strength training during the preceding 6 months (≤1 session·week-1). During the five weeks leading up to the intervention, STR and CON had a mean weekly amount of unspecific core and stability training of 0.7 ± 0.7 h and 1.0 ± 1.4 h, respectively (no differences in h between groups: *P* = 0.46).There were no differences in total yearly training volume between strength (STR) and control (CON) group (639 ± 136 h and 530 ± 202 h, respectively, *P* = 0.77). Furthermore, there was no difference between the groups in either weekly training hours (STR; 15.6 ± 11.5 h and CON; 14.7 ± 10.6 h, *P* = 0.41) or its distribution into low- (68-82% of maximum heart rate (HRmax)), moderate- (83-87% of HRmax) and high-intensity (88-100% of HRmax) training during the 4 weeks leading up to pre-testing. Due to the limited number of potential high performance level participants, we were unable to perform a fully randomized study as some participants conditioned their partaking on being able to perform their scheduled training regime. The participants were therefore allowed to choose which study group they would be part of. Two participants did not complete the study due to illness and injury during the course of the intervention period and their data were excluded from the analyses.

(Insert table 1 approximately here)

*Experimental design*

Participants were tested pre and post to an 8-wk strength training intervention, with testing conducted over two days, separated by 24-48 h. On test day 1, maximal strength testing was followed by 1 h of recovery before a blood-lactate profile and an incremental time-to-exhaustion (TTE) test was done using the DP-technique while treadmill roller skiing (Figure 1). On test day 2, the participants performed a 90 min prolonged DP test, followed by the same incremental TTE test performed at test day 1. During the 8-wk intervention, participants in the STR groups added either traditional heavy strength training or the exact same heavy strength training with superimposed vibration to their on-going endurance training. The participants in CON continued their usual endurance training without any additional strength training, but was allowed to perform whole body stability and core training. The intervention period started 5 wks after the competitive season ended.

(Insert figure 1 approximately here)

*Training*

Strength training included standing double poling, seated pull down and triceps press, performed in that order three times per week. The strength training was performed as a daily undulating periodization program[23] with a progression towards fewer repetitions and higher loads. The first and last weekly session was performed to failure and the load was adjusted according to the repetition maximum (RM) principle. The second strength session each week was executed with ~10% reduced load in comparison to the predicted RM (i.e. sets were not performed to failure). During the first 3 weeks, skiers performed 10, 12 and 6 repetitions during the 1st, 2nd and 3rd strength training session of the week, respectively. During the following 3 weeks, repetitions were adjusted to 8, 10 and 5 repetitions for the 1st, 2nd and 3rd session, respectively, which was further adjusted to 6, 8 and 4 repetitions for the final two weeks. The skiers were instructed to perform the strength training with maximal acceleration and speed during the concentric phase (lasting around 1 s), while the eccentric action was performed more slowly (i.e. lasting around 2-3 s). The number of sets in each exercise was always three, and the inter-set rest periods were 2-3 min. The skiers were encouraged to continuously increase their RM loads throughout the intervention period and they were allowed assistance on the last repetition.

At the start of each strength training sessions, skiers performed a ~10 min warm-up at a self-selected intensity on a stationary cycle ergometer or treadmill, followed by two warm-up sets of a gradually increasing load performing seated pulldown. Before the standing double poling and triceps press exercises one warm-up set at moderate load was performed. All exercises used a custom-made handlebar connected to the wire on the pulldown apparatus designed to imitate pole-grip and shoulder movement of DP in XC-skiing [7]. The exercises were executed as described in Losnegard et al. [7]. To secure proper technique in standing double poling the exercise was modified with a bench to stabilize the pelvis. The vibration group performed the exact same strength-training programme as explained above, with the only difference being the addition of superimposed vibrations of 50 Hz to the wire in a custom made pulldown apparatus as done previously by Nygaard & Rønnestad [24]. All workouts were supervised by an investigator and all skiers kept detailed training logs during the course of the intervention. To ensure adequate protein intake in connection with the strength training sessions, the skiers in the STR group consumed a 100 g protein-chocolate bar containing 30 g protein and 411 calories immediately after the sessions (“Big Bar 100”, Proteinfabrikken, Norway). On days where both endurance and strength training sessions were performed, the skiers were encouraged to perform strength training in the first session of the day.

Testing

Tests were performed with the exact same order and procedures pre and post to the 8-week intervention. Skiers were instructed to refrain from intense exercise (<80% HRmax) the day preceding test days, to consume the same type of meal before testing, and to avoid eating or consumption of coffee or other products containing caffeine during the last 3 h before a test. All tests were performed under similar environmental conditions (17-19ºC) and at approximately the same time of the day to avoid circadian variance (±1-2 h). All DP tests were performed on the same roller-ski treadmill (Rodby RL2500E, Rodby Innovation AB, Vänge, Sweden). To exclude variation in rolling resistance, each skier used the same roller skis (Swenor-fiberglas, 2150 g each pair, Sport Import AS, Sarpsborg, Norway) with wheel type 2 and the warm-up of the wheels was standardized by a 10-min warm-up before each test [25]. Each skier used their own ski poles, with custom made carbide tips, adjusted for their individual body height.

*Test day 1*

Maximal strength

Maximal strength was measured as 1RM in seated pulldown and triceps press using the same custom-made handlebar as in training [7]. Strength tests were always preceded by a 10-min warm up on a cycle ergometer followed by four standardized exercises with the purpose to activate the main muscle groups of the upper-body (10 x counter movement jump, sit-ups, push-ups and back hyperextension). Thereafter, a standardized protocol consisting of two sets of 10 and 6 repetitions with 65 and 75% of predicted 1RM was performed. This protocol was performed before 1RM test in both exercises. The details of the 1RM protocol and criteria for accepted lifts in seated pulldown are described elsewhere [7]. For seated pulldown and triceps press a GYM2000 pulldown apparatus (GYM2000 AS, Vikersund, Norway) was used. The movement in triceps press started with the elbows flexed to 130-140º, followed by pulling the handlebar towards the hipbone. The handlebar had to be pulled completely down in one continuous motion with the hands parallel to be accepted as 1RM. The pre- and post-intervention tests were conducted using the same equipment with identical positioning of the skiers relative to the equipment and monitored by the same experienced investigator. Verbal encouragement was standardized under the tests.

Blood lactate profile test

One hour after the maximal strength tests, the skiers performed a blood lactate profile test while treadmill DP. The test started with a 10 min warm-up on 3% inclination and 12 km·h-1 before the treadmill was adjusted to 6% inclination. Each skier started at 10 km·h-1 and the speed increased with 2 km·h-1 every 5 min. Blood was sampled from a fingertip at the end of each 5-min bout and analysed for whole blood lactate concentration ([la-]) using a Biosen C-line lactate analyser (EKF Diagnostic BmbH, Barlebe, Germany). At the same time, rating of perceived exertion (RPE) was recorded through Borg’s 6-20 scale (Borg, 1982). The test was terminated when a [la-] of >4 mmol·L-1 was measured. Oxygen consumption (VO2) and respiratory exchange ratio (RER) were measured during the last 3 min of each bout using a computerized metabolic system with a mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). Mean values of VO2 and RER were used for statistical analysis. The power output at 4 mmol·L-1 [la-] was calculated from the relationship between [la-] and power output using linear regression between data points. Power output was calculated as the sum of power against gravity and the power against roller friction in a coordinative system moving with the treadmill belt at a constant speed [25]. The lactate analyzer and metabolic system were calibrated according to the instruction manual and as described in detail by Losnegard et al. [7], repectively. The computerized metabolic system has shown to be accurate for measuring oxygen uptake during shorter and longer periods [26]. The treadmill speeds of 10 and 12 km·h-1 corresponded to an average relative intensity of ~75 and 85% of HRmax respectively. Subsequently, submaximal steady-state VO2, RER, HR, [la-] and RPE were assessed at these intensities on test day 1. HR was measured using a Polar S610i HR monitor (Polar, Kempele, Finland).

Time to exhaustion test

After termination of the blood lactate profile test, the skiers exercised for 10 min at a submaximal speed (12 km·h-1 – 3% inclination) before completing an incremental DP test to exhaustion for determination of TTE (as an indicator of performance) and peak oxygen uptake (VO2peak). The test started at 10 km·h-1 and 6% inclination, and speed was increased with 1 km·h-1 every minute until exhaustion. The test was terminated when the front wheels passed a marker placed 100 cm behind the front end of the treadmill and the completed seconds during the test determined TTE. VO2peak and RERmax were calculated as the average of the two highest 30-s measurements. Directly after the test, RPE, [la-] and peak heart rate (HRpeak)were determined.

*Test day 2*

Prolonged submaximal DP followed by TTE test

The same warm-up protocol as test day 1 was performed followed by 90 min DP at 6% inclination and a workload (speed) equivalent to 65% of VO2peak. Workload was individually calculated by using the linear relationship between workload and oxygen cost from the blood lactate profile on test day 1. The same absolute workload for each individual skier was used in the post-intervention test, independent of change in the lactate profile test or VO2peak. Immediately after the 90 min DP, the protocol utilized for the blood lactate profile on test day 1, including the 10 min warm-up, was repeated until reaching [la-] ≥4 mmol·L-1. VO2, RER, HR, RPE and [la-] were determined during 3-min periods at 8 different time points ending at 5, 20, 40, 60, 80, 90 min of the 90 min submaximal DP and at the two first stages of the blood lactate profile test (105 and 110 min). The first two stages in the blood lactate profile test were completed by all skiers and were therefore used in the statistical analyses. Before commencing the TTE test, each skier completed the same number of stages of the blood lactate profile at post-test as they did during the pre-test. To maintain fluid balance and mimic race condition skiers drank water *ad libitum*. The same amount and time of ingestion of fluid was completed at post-test. As an indication of performance-ability with or without prolonged submaximal DP, the effect of prolonged submaximal DP on time to exhaustion was determined by subtracting TTE day 2 from day 1 and expressed as TTEdiff.

Double poling kinematics

Ten DP cycles at six time-points (5, 20, 40, 60, 80, 90 min) during the prolonged submaximal DP test were analysed for determination of cycle time, cycle length (m) and cycle frequency (Hz) using high resolution video recordings (1080p resolution, 30 frames per second, GoPro Hero+ , San Mateo, CA, USA) and Kinovea motion analysis software (version 0.8.15, available for download at: http://www.kinovea.orghttp://www.kinovea.org).

Electromyography of m. triceps brachii

Surface EMG activity was recorded by a Telemyo DTS wireless system (Noraxon Inc., Scottsdale, Arizona, USA) for m. triceps brachii (TB) located in the posterior (extensor) compartment of the arm. A pair of dual surface electrodes, product 272 (Myotronics Inc., Kent, WA, USA) was attached to the skin with a 20-mm inter-electrode distance. The electrodes were placed according to SENIAM (surface EMG for a non-invasive assessment of muscles) longitudinally with respect to the underlying muscle fibre arrangement and placed on m. triceps brachii long head [28, 29]. EMG reference points for electrode positions were photographed to secure similar electrode placement at the post-test. Prior to the electrode application, the skin was shaved and cleaned with alcohol to minimize impedance [30]. The recorded EMG-signals were sampled at 1500 Hz, high-pass filtered using a cut-off frequency of 10 Hz and low-pass filtered using a 500 Hz cut off frequency, and smoothed over 100 ms (root mean square algorithm). EMG measurements were recorded and 10 subsequent DP cycles were averaged during the last min at the time points 5, 20, 40, 60, 80, 90 min. EMG data were expressed as standard amplitude parameters; peak values (EMGpeak (µV)), the slope (EMGslope (µV/sec)) and area (EMGarea (µV·sec)) [30]. Peak values were chosen to visualize the highest activation level in a DP cycle – independent of the time. Slope was used because it may indicate fatigue during the tests: less incline means slower muscle (neural) activation (not only lower activation levels). Area values were used to describe the total muscle activation and to evaluate changes in duty cycle of the poling technique. Furthermore, the EMG parameters from TB was normalized by dividing the value from each time point (20, 40, 60, 80, 90 min) by its own EMG value obtained during the last min at the 5-min time point [11, 31, 32].

Near-infrared spectroscopy

Near-infrared spectroscopy (NIRS) was used to continuously measure changes in muscle oxygen saturation during all DP exercise tests. Three portable NIRS devices (Portamon, Artinis Medical Systems, Netherlands) generating light at two wavelengths (845 and 761 nm) were used to monitor changes in muscle saturation of the TB (placed on the muscle belly of the TB, just proximal of the triceps tendon, on top of the long and lateral heads of the muscle), latissimus dorsi (LAT), and vastus lateralis (VL) muscles. All NIRS devices were placed directly on the skin on top of the muscle belly, fixed with adhesive tape, and covered with a bandage. Each of the Portamon devices contained three LED transmitters and one receiver with fixed source-detector distances of 30, 35 and 40 mm. Spatially resolved spectroscopy (SRS) was used to measure tissue oxygen saturation (SmO2). Simultaneous NIRS measurements on all three muscles were done with one operating system. Data were sampled at 10 Hz, displayed real-time and stored on disk for off-line analysis. Adipose tissue thickness (ATT) was measured after test day 1, on top of each muscle and in between source and detector using a skinfold caliper (Holtain Ltd, Crymmych, UK). ATT was 3.6 ± 0.6 mm for TB, 3.6 ± 0.3 mm for LAT and 5.1 ± 0.6 mm for VL in STR, and 3.0 ± 0.9 mm for TB, 3.8 ± 0.4 mm for LAT and 3.9 ± 0.9 mm for VL in CON.

Baseline muscle saturation levels (SmO2) were calculated for each subject as the mean over a 30-sec period prior to the DP exercise tests on day 1. Maximum changes in saturation were calculated as the difference between start and end-exercise desaturation levels during the VO2max test. End-exercise values were calculated as the mean over the last 30 sec of the VO2max test. During the prolonged submaximal DP, changes in tissue saturation were calculated as the mean over a 60-sec period corresponding the time periods used to calculate the other variables (i.e. at 5, 20, 40, 60, 80, 90 min). Due to missing NIRS data and cross talk between PortaMon devices, a total of 18 and 7 skiers in STR and CON, respectively, were included in the NIRS statistical analyses.

Dual-energy x-ray absorptiometry (DXA)

Changes in lean body mass (LBM) was measured with DXA Lunar Prodigy densitometer (Prodigy Advance PA+302047, Lunar, San Francisco, CA, USA). The skiers were not allowed to eat or drink the last two hours before each DXA scan. Unfortunately, it was not possible to perform DXA scan for CON.

Statistics

All data are presented as mean ± standard deviation (SD), unless otherwise stated. To test for differences between groups at baseline, a one-way ANOVA was employed. Since no differences in adaptations between the group that performed traditional strength training and the group that added superimposed vibration to the same strength training occurred, further analyses were performed with all athletes pooled into one strength group, STR. Differences in the percentage change between STR and CON in performance was tested with an unpaired student’s t-test and within-group changes were analysed using a paired student’s t-test. Percentage changes from pre- to post-test in physiological variables, EMG, NIRS and DP kinematics were analysed by a two-way repeated measures ANOVA (group (2) x time points (6)), with Bonferroni’s *post hoc* tests to localize differences between groups. Absolute changes were analysed by two-way repeated ANOVA (time points (6) x training intervention (post vs pre)). NIRS variables were analysed by a three-way repeated measures ANOVA (group x time x muscle). Effect sizes (ES) were calculated as Cohen’s *d* and interpretations of the magnitude were as following: 0-0.2 = trivial, 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large and > 2 = very large [33]. Analyses were performed in SPSS version 23.0 (Chicago, IL), and in Excel 2013 (Microsoft Corporation, Redmond, Washington). All analyses resulting in *P* < 0.05 were considered statistically significant. P-values < 0.10 were considered as tendencies.

**Results**

*Maximal strength and lean body mass*

All skiers in the STR group performed at least 16 of 24 strength-training sessions, resulting in 89 ± 11% adherence to the strength training. No significant differences were found between the group who added vibration to their strength training and traditional strength training in changes in seated pull-down (7.8 ± 5.6% vs. 10.5 ± 3.9%, *P* = 0.72) and triceps press (20.6 ± 9.1% vs. 21.2 ± 12.7%, *P* = 0.95). In addition, we found no changes across groups for any test variable, and data from these two groups were therefore pooled into one STR group in the further analyses.

There were no group differences in maximal strength (or other measures) at baseline (Table 1). During the intervention period STR had a larger improvement in 1RM in seated pull-down (8.9 ± 4.4%) and triceps press (21.7 ± 10.8%; both *P* < 0.01) than CON (*P* = 0.023 and P < 0.01, respectively) where no significant changes occurred (seated pull-down: 0.8 ± 4.5%, triceps press: 4.8 ± 6.4%). Upper-body LBM increased by 2.8 ± 2.9% in STR (n=13, *P* = 0.006) from pre- to post-test, with body mass being unchanged in both STR (pre: 77.3 ± 7.6 kg, post: 78.3 ± 7.8 kg, *P* = 0.98) and CON (Pre: 76.7 ± 7.8 kg, post: 76.7 ±7.6 kg, *P* = 0.72).

*Training hours*

During the intervention period there was no significant difference in weekly duration of endurance training or the distribution of this training within the low, medium and high intensity zone between STR (13±3 h, 1±1 h and 1±1 h, respectively) and CON (10±5 h, 1±1 h and 1±0 h, respectively). In addition, no difference was found in weekly time spent as running, cycling, DP or other skiing training between STR (4±1 h, 1±1 h, 2±2 h and 7±2 h, respectively) and CON (4±1 h, 1±1 h, 2±2 h and 5±2 h, respectively).

*VO2peak and time to exhaustion*

There was no change in VO2peak from pre- to post-test in either STR (68.5 ± 5.3 vs. 68.3 ±5.4 mL.kg-1.min-1, *P* = 0.9) or CON (66.3 ± 7.9 vs. 66.6 ± 8.2 mL.kg-1.min-1, *P* = 0.68). TTE during the same test (day 1) improved by 9.6 ± 8.5% and 7.6 ± 5.4% in STR and CON (both *P* < 0.05), with no differences between the groups` improvement (*P* = 0.55; Figure 2).

STR improved TTE following prolonged submaximal DP by 19.6 ± 16.0% (*P* < 0.01), an improvement tending to be larger (*P* = 0.07) than for CON (8.8 ± 17.7%, *P* = 0.13). This tendency showed a moderate practical effect of STR compared to CON (ES = 0.80; Figure 2). TTEdiff did not differ between STR and CON at pre-test (-1.04 ± 1.21 min and -1.29 ± 1.37 min, respectively, *P* = 0.66). However, at post-test TTEdiff was significantly reduced in STR compared to CON (-0.45 ± 0.58 min and -1.32 ± 1.22 min, respectively *P* = 0.049).

(Insert figure 2 approximately here)

*Blood lactate profile*

There were no between-group changes in VO2, RER, HR, [la-], RPE during 10 and 12 km·h-1 at test day 1. No difference between groups was seen in changes in power output at 4 mmol·L-1 [la-]. From pre- to post-test STR significant reduced VO2-consumption and HR at 10 km·h-1 (from 40.0 ± 2.5 to 38.2 ± 1.7 mL·kg-1·min-1 and from 146 ± 18 to 135 ± 16 beats·min-1, respectively) and 12 km·h-1 (46.6 ± 1.9 to 44.7 ± 2.6 mL·kg-1·min-1 and from 157 ± 17 to 150 ± 16 beats·min-1, respectively; all *P* < 0.05). The same was seen in CON at 10 km·h-1 (from 41.4 ± 2.5 to 38.3 ± 1.9 mL·kg-1·min-1 and from 141 ±16 to 129 ± 12 beats·min-1) and 12 km km·h-1 (from 47.2 ± 2.7 to 44.9 ± 3.0 mL·kg-1·min-1 and from 154 ± 14 to 143 ± 15 beats·min-1, respectively; all *P* < 0.05). Both STR and CON increased power output at 4 mmol·L-1 [la-] from pre- to post-test, (from 243±46 W to 261±57 W and from 219 ± 48 W to 242 ± 54 W, respectively, both *P* < 0.05).

*Physiological responses during prolonged submaximal DP*

There was no significant difference in changes from pre to post between the two groups in any of the measured variables (*P* > 0.05), except that CON had a larger increase in RER at 90 min and during the first fixed stage (105 min, table 2). From pre to post, both STR and CON improved on several variables at different time points (Table 2). Furthermore, only STR reported reduced rating of perceived exertion the last 20 min (from 80-110 min) of the prolonged submaximal DP (*P* < 0.05).

(Insert table 2 approximately here)

*Electromyography and kinematics during prolonged submaximal DP.*

There were no differences between the groups in changes in EMG parameters expressed as EMGpeak, EMGslope and EMGarea (all *P* > 0.05, table 2). Furthermore, were there no changes in between or within the groups in DP kinematics (i.e., cycle rate, length and time) (all *P* > 0.05).

*Near-infrared spectroscopy*

*Pre-training desaturation responses.* Pre-training resting muscle saturation (SmO2rest) was similar in both groups (*P* = 0.54), and all muscles (*P* = 0.42). SmO2rest was 67.5 ± 1.8%, 68.8 ± 2.9% and 69.0 ± 2.3% for TB, LAT and VL, respectively. Maximum desaturation (SmO2max) was similar in both groups (*P* = 0.71), but differed for the three muscles (*P* = 0.01) being largest in LAT as compared to TB and VL (both *P* < 0.05), with no differences between TB and VL (*P* = 0.57). The decrease in SmO2max was -23.6 ± 4.4%, -28.6 ± 5.3% and -20.8 ± 3.1%, for TB, LAT and VL, respectively. Desaturation responses during the prolonged submaximal DP were similar in both groups (*P* = 0.34), but changed during the test and differed between muscles (both *P* < 0.001). There was an interaction effect of muscle x time (*P* < 0.001) with higher desaturation levels in TB and LAT as compared to VL (both *P* < 0.001).

*Effect of strength training on desaturation responses.* No effect of strength training was found on baseline saturation levels (SmO2rest). SmO2rest was not different between pre- and post-measurements (*P* = 0.55), neither between STR and CON (*P* = 0.42), nor between the three muscles (*P* = 0.47). SmO2max was not different between STR and CON (*P* = 0.23), but, a tendency existed for a slightly more pronounced desaturation during the post-test measurements (*P* = 0.07), though this effect was similar in both groups (*P* = 0.47). The differences in SmO2max found between the muscles during pre-test measurements were still present during post-test measurements (*P* = 0.02), showing no effect of strength training (*P* = 0.28). Group mean SmO2 responses for both groups and all muscles during pre- and post-conditions are shown in figure 3. As can be seen in figure 3, desaturation levels changed during the prolonged submaximal DP (*P* < 0.001), and this response was different for the three muscles (*P* < 0.001). For TB and VL, SmO2 responses were similar in both groups and no effect of strength training was found (all *P* > 0.05). For LAT, there was a different response between STR and CON (P = 0.03), with an improvement in SmO2 throughout the 90-min test in STR, which was less clear in CON. In addition, there was a tendency for a difference between pre- and post-training measurements in CON (P = 0.09) suggesting that the lack of improvement in SmO2 (as shown in STR) is mostly due to the post-test response in CON where an improved SmO2 throughout the 90-min test was absent.

(Insert figure 3 approximately here)

**Discussion**

The primary findings of the present study were: a) Superimposed vibrations during the strength training did not induce any additive effect on any of the strength or endurance tests compared to similar strength training without vibration; b) STR tended to improve DP performance (i.e. TTE) after prolonged submaximal DP more than CON, with the effect size revealing a moderate practical effect; c) STR improved TTEdiff more than CON following the intervention; d) There were no group differences for changes in traditional determinants of endurance performance.

This is, to our knowledge, the first study to compare the effects of adding vibration to upper-body strength training in XC-skiers, we found no ergogenic effect of adding vibration on 1RM compared to the same strength training regime without vibration. This is in contrast to previous observations where superimposed vibrations acutely increased maximal force and power output [19-21] and also induced superior strength training adaptations [22], but in agreement with the observation of unaltered adaptations by vibrations in long distance runners performing heavy strength training with or without adding whole-body vibration [34]. We found a 9-22% increase in 1RM for STR in seated pulldown and triceps press from pre-to post-test, findings that agree with comparable studies showing 10-24% strength gains over 8-12 weeks in upper-body strength for well-trained XC-skiers [7, 12, 13, 15, 35]. The observed increase in 1RM for STR after 8 weeks of progressive strength training coincided an increase in upper-body LBM. Although we did not have LBM data from CON, their lack of changes in 1RM indicates that this factor most likely did not change.

The present study showed that STR tended to have a larger improvement in performance, measured as TTE following prolonged submaximal DP on roller skis, than CON. This is the first study to examine performance after long duration exercise in XC-skiing, and indicates that heavy strength training positively influence performance following long-lasting exercise. This is further supported since no significant difference was found between groups for the same test performed in a more rested state. In the latter case, our data support previous studies measuring the effect of strength training on performance on roller skis, where no significant ergogenic effect of strength training in male XC-skiers was reported [7, 15, 16]. In comparison, some studies observed superior effect of concurrent strength and endurance training on time trails or TTE in DP ergometers [7, 12-14]. In all of these previous studies, performance tests were performed without an initial prolonged exercise and their findings are therefore difficult to compare with our TTE-test performed after prolonged exercise.

The present observation of advantage of strength training on performance following prolonged submaximal exercise has previously been observed in two studies on cyclists with similar test protocols. In those studies, concurrent strength and endurance training induced significantly better 5-min all-out performance following 3 hours submaximal cycling compared to endurance training only [17, 18]. In these two studies, group differences in work economy occurred during the last 1-2 hours of the prolonged test when the cyclists started to get some exhaustion. In the present study, VO2 and HR were reduced at all time-points during the post-test, but no difference was seen between the two groups. In previous studies on XC-skiers, work economy measured while roller skiing remained unaltered after strength training interventions [7, 15, 16], whereas improved economy have been observed when work economy was measured in double poling ergometers [12-14]. While no difference in work economy occurred between groups in our study, both groups improved this factor from pre- to post-test. This is likely caused by a change in the training content during the intervention period, with more DP on roller skis (average 2 hrs·wk-1)as compared to the active recovery period leading up to the intervention. However, changes in work economy were not followed by cycle length or rate alternations during the prolonged submaximal DP for any of the groups. DP kinematics may be difficult to alter during such a short period, especially in technically well-developed XC-skiers. It would have been interesting to perform a follow-up test after several weeks with maintenance of the increased strength to investigate whether it can improve the technique in the long term. The positive effects of increased strength could rather have induced the ability to use relatively less muscle force to sustain the same gross kinematic pattern at a given intensity at post-test.

Unlike the studies on cyclists [17, 18], the superior change in TTE performance following prolonged submaximal DP in STR could not be explained by changes in physiological responses during the preceding prolonged submaximal DP. One mechanism that could explain the presence of superior TTE, is the possibility of improved anaerobic capacity due to increased LBM [36], in combination with a larger force potential achieved by increased 1RM strength. Furthermore, increased strength of type I muscle fibres can, in theory, allow STR to use the more economical type I muscle fibres for a longer duration, and therefore delayed recruitment of type II muscle fibres [37]. In this connection, reduced EMG activity has been observed in the m. vastus lateralis during the last hour of two hours of submaximal cycling following 5 weeks of strength training in well-trained triathletes, indicating delayed recruitment of type II fibres [11]. However, in the present study, no statistical differences were seen in EMG patterns between or within the groups from pre- to post-test. We do note that STR achieved a numerical reduction in EMGarea that was 9- and 7%-points lower than CON at 105 and 110 min, respectively, but the statistics do not allow us to speculate whether this could be related to a small reduction in activation of type II fibres at post-test. Interestingly, STR reported a significant lower RPE at all time-points during the prolonged submaximal DP at post-test, whereas there was no significant change from pre- to post-test in CON during the last 20 min of the prolonged test. Although the change was not significantly different between the groups, one interpretation is that STR were further from exhaustion at the end of the prolonged submaximal DP and therefore were more likely to perform better during the following TTE test. This is supported by the hypothesis that, due to the proposed linear increase in RPE over exercise time, RPE is a sensitive predictor of time to exhaustion [38]. The suggestion that STR was further from exhaustion than CON at the end of the prolonged submaximal DP at post-test is supported by the significantly larger reduction in TTEdiff in STR vs. CON. In agreement with the latter, is the slightly more pronounced desaturation seen in CON compared to STR that might reflect more exhausted muscles in CON vs. STR during and at the end of prolonged submaximal DP, thus creating less optimal conditions in CON at the start of the TTE test.

There was no difference in VO2peak from pre- to post-test in either of the groups. This is in line with most previous strength training studies on XC-skiers [12-14, 16, 39], although Losnegard et al. [7] found an increase and Skattebo et al. [35] a reduction of VO2max after 10-12 weeks of concurrent strength and endurance training. Furthermore, there was no difference between our groups in the change in power output at 4 mmol·L-1 [la-], a finding that agrees with other studies on XC-skiers [7, 12, 14-16, 39]. Some limitations of the present study may be related to the experimental design, specifically the relatively short intervention period (8 weeks), lack of randomization into groups, protein supplements only to the STR group, and lack of LBM data from CON. In the current study, we examined treadmill DP at 6% incline. Although XC skiers DP at such inclines in competitions, they also use DP at lower inclines and higher speeds with reduced poling times and larger demands of rapid force generation [40]. Whether strength training would have influenced DP performance on lower inclines differently is currently unknown. Furthermore, DP intensity in long distance races will, as in normal distance races, vary with differences in the skiing terrain where uphill terrain demands high intensities, close to VO2max, with downhill terrain resulting in lower intensities [2]. This variation in inclination and intensity during the initially prolonged DP test was not adjusted for in our design. Nevertheless, the present findings of STR tending to improve DP performance (i.e. TTE and TTEdiff) after prolonged submaximal DP more than CON, with the effect size revealing a moderate practical effect, following the intervention are novel and provide a basis for further exploring the effects of strength training in XC skiers.

In conclusion, the present study indicates that adding strength training to endurance training in well-trained XC skiers leads to improvements in 1RM strength, DP performance following prolonged submaximal DP and TTEdiff, indicating a specific effect of strength training on the ability to maintain performance after long-lasting exercise.

*Perspective*

It is important to keep in mind that aerobic endurance training is the most important training stimulus for XC-skiers. Based on the results from the current study, XC-skiers should consider to include upper-body strength training in their training programs to maximize their DP performance after long-lasting exercise. Interestingly, no additive effect of strength training was observed during the lab assessment of traditional determinants of endurance performance, indicating that it might be important with prolonged exercise (as in races) before a beneficial effect of strength training can be observed. The observation that adding vibrations to upper-body strength training in well-trained XC-skiers did not affect strength or endurance adaptations, indicates that skiers should not give priority to this training mode. The long-term effects of strength training (including lower-body muscles) on XC-skiers have not yet been reported and should be further elucidated. Also, the effect of strength training on performance after prolonged exercise in other skiing techniques than DP should be investigated.

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**Figure legends**

**Figure 1** Experimental design with maximal strength and physiological performance variables measured during two separate test days pre and post to 8 weeks of heavy upper-body strength training with or without vibration. RM: repetition maximum, TTE: time to exhaustion, DP: double poling.

**Figure 2** Time to exhaustion (TTE) presented as individual (dotted lines) and mean values (solid lines) pre and post to the 8-week intervention period for skiers adding strength training to their normal endurance training (STR, panels to the left) and skiers performing normal endurance training only (CON, panels to the right). Upper panels illustrates TTE performed in rested state (test day 1) and lower panels illustrates TTE after prolonger submaximal exercise (test day 2). \*Different from pre (*P* < 0.05). # Tendency to be different from CON (*P* = 0.07).

**Figure 3** Group mean (±SD) values for changes in muscle O2 saturation (SmO2) in the m. triceps brachii (TB; A, B), m. latissimus dorsi (LAT; C, D) and m. vastus lateralis (VL; E, F) during prolonged submaximal DP exercise for skiers adding strength training to their normal endurance training (STR; A, C, E) and skiers performing normal endurance training only (CON; B, D, F). Pre-test SmO2 values in filled circles, post-test SmO2 values in open circles. \* *P* < 0.05 for the interaction effect of time (in minutes) x period (pre- vs. post-test measurements).