MASTERGRADSOPPGAVE

Effects of upper body sprint interval training on endurance performance, aerobic capacity and work economy in female cross-country skiers during classical roller skiing

Effekter av sprintintervalltrening for overkroppen på utholdenhetsprestasjon, aerob kapasitet og arbeidsøkonomi hos kvinnelige langrennsløpere på klassisk rulleski

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2015

MKØ210

Mastergradsoppgave i kroppsøving- og idrettsvitenskap

Avdeling for lærerutdanning

Høgskolen i Nord-Trøndelag - 2015

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Master's degree in Physical Education and Sport Science Department of Teacher Education Nord-Trøndelag University College

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SAMTYKKE TIL HØGSKOLENS BRUK AV MASTEROPPGAVE

Forfatter:

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Engelsk tittel:

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ABSTRACT

Introduction: Sprint interval training (SIT) in running and cycling has shown to induce larger metabolic and performance adaptations than continuous endurance training (CET), and may additionally be more effective than CET in improving anaerobic performance and neuromuscular factors. However, limited research is done on the effects of SIT during upper body exercise. **Purpose:** To compare the effects of upper body SIT with CET in improving endurance performance, peak aerobic capacity, work economy and kinematics in classical roller skiing, as well as upper body strength and power among endurance trained female athletes. **Methods:** 17 highly trained junior female cross-country skiers (age: 18.1±0.8yrs, maximal oxygen uptake (VO_{2max}): 3.30±0.37 $L{\cdot}min^{-1}$) performed an 8-week intervention training period where the sprint interval training group (SIG, n=8) added 2 weekly sessions of six to eight 30-s maximal upper body intervals either using roller board in kneeling position or by roller ski double poling (DP). The control group (CG, n=9) added a weekly session of 45-75min of continuous low-intensity DP on roller skis. Before and after the intervention, the subjects were tested for peak velocity, peak aerobic capacity, work economy, physiological and kinematical responses during incremental DP and diagonal stride (DIA) treadmill roller skiing tests. Additionally, maximal upper body strength (1RM) and average power 40% 1RM in a poling specific strength exercise was measured. **Results:** There were no significant group effects on the pre-to post-changes in peak velocity in DP or DIA, although CG increased DP peak velocity by 4.5±3.5% (P=0.011). Both groups improved DP VO_{2peak} by 0.3±0.2 $L{\cdot}min^{-1}$ in SIG and 0.2±0.2 $L{\cdot}min^{-1}$ in CG (both P<0.05). The increases in DP VO_{2peak} did not significantly differ between groups. SIG was more effective than CG in improving DIA VO_{2max} (+0.2±0.1 $L{\cdot}min^{-1}$; P=0.033). Additionally, SIG improved 1RM more than CG (+3.2±1.4 kg; P=0.03), with the same tendency occurring for average power (+12.1±5.9 W; P=0.057). Work economy and kinematics (cycle length or rate) did not change significantly within or between groups in any case. **Conclusion:** Both groups improved peak aerobic capacity in DP, but no significant group differences were found in endurance performance, work economy or kinematics in neither DP nor DIA roller skiing. SIG had larger increases than CG in DIA VO_{2max}, as well as in upper body maximal strength and power. These findings indicate a large potential for female junior skiers to improve their physiological capacities by increased focus on upper body training in general, and that SIT tends to be particularly effective for improving strength and power characteristics. **Key words:** interval training; cross-country skiing; endurance performance; upper body; female athletes.

NORSK SAMMENDRAG

Introduksjon: Sprintintervalltrening (SIT) i løping og sykling har vist å indusere større metabolske- og prestasjonsadaptasjoner enn kontinuerlig utholdenhetstrening (CET), og kan i tillegg være mer effektiv enn CET i å forbedre anaerob prestasjon og nevromuskulære faktorer. Det er imidlertid begrenset forskning som har undersøkt effektene av SIT på overkroppen. **Formål:** Å sammenligne effekter av SIT på overkroppen med CET i å forbedre utholdenhetsprestasjon, peak aerob kapasitet, arbeidsøkonomi og kinematikk i klassisk rulleski, samt overkroppsstyrke og -power blant utholdenhetstrente kvinnelige idrettsutøvere. **Metode:** 17 veltrente kvinnelige junior langrennsløpere (alder: 18.1±0.8 år, maksimalt oksygenopptak (VO_{2max}): 3.30±0.37 L·min^{-1}) gjennomførte en 8-ukers intervensjonstreningsperiode hvor sprintintervalltreningsgruppen (SIG, n=8) la til 2 ukentlige økter bestående av seks til åtte 30-s maksimale overkroppsintervaller utført enten ved knestående bråsterk eller på rulleski staking (DP). Kontrollgruppen (CG, n=9) la til en ukentlig økt ved 45-75min kontinuerlig lav-intensitet DP på rulleski. Før og etter intervensjonen ble subjektene undersøkt for peak hastighet, peak aerob kapasitet, arbeidsøkonomi, fysiologiske og kinematiske responser ved trinnvise rulleskitester i DP og diagonalgang (DIA) på tredemølle. I tillegg ble maksimal overkroppsstyrke (1RM) og gjennomsnittlig power ved 40% av 1RM i en stakespesifikk styrkeøvelse undersøkt. **Resultat:** Det var ingen signifikant gruppeeffekt på pre-til post endring i peak hastighet i DP eller DIA, selv om CG økte peak hastighet i DP med 4.5±3.5% (P=0.011). Begge gruppene forbedret DP VO_{2peak} med 0.3±0.2 L·min^{-1} i SIG og 0.2±0.2 L·min^{-1} i CG (begge P<0.05). Økningene i DP VO_{2peak} utgjorde ingen signifikant forskjell mellom gruppene. SIG var mer effektiv enn CG i å forbedre DIA VO_{2max} (+0.2±0.1 L min^{-1}; P=0.033). I tillegg forbedret SIG 1RM mer enn CG (+3.2±1.4; P=0.03) med samme tendens for gjennomsnittlig power (+12.1±5.9W; P=0.057). Arbeidsøkonomi og kinematikk (sykluslengde eller frekvens) endret seg ikke signifikant, verken innenfor eller mellom gruppene i ethvert tilfelle. **Konklusjon:** Begge gruppene forbedret peak aerob kapasitet i DP, men ingen signifikant gruppeforskjell ble funnet for utholdenhetsprestasjon, arbeidsøkonomi eller kinematikk i verken DP eller DIA på rulleski. SIG hadde større økning enn CG i DIA VO_{2max}, samt i maksimal styrke og power på overkroppen. Disse funnene indikerer et stort potensial for kvinnelige junior skiløpere i å forbedre deres fysiologiske kapasitet ved økt fokus på trening av overkroppen generelt, og at SIT tenderer mot å være spesielt effektiv i å forbedre styrke- og powerkarakteristikker. **Nøkkelord:** intervalltrening; langrenn; utholdenhetsprestasjon; overkropp; kvinnelige idrettsutøvere.

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1.0 INTRODUCTION

Cross-country skiing is a physically and technically demanding endurance sport where combined upper-body poling and leg push-offs produce forward propulsion. In a variety of competition forms (lasting from ~3 - >120 minutes) skiers constantly alternate their technique according to changes in velocity and track incline, and skiers select between different sub-techniques in order to optimize locomotory efficiency and performance [1-4]. Energy delivery capacity and mechanical efficiency are two key factors of cross-country skiing performance [5, 6]. Cross-country skiing is regarded as one of the most demanding endurance sports, and high-level skiers are among the athletes with the highest maximal oxygen uptake (VO_{2max}) [7-9]. Additionally, the fractional utilization of VO_{2max} [10] in specific techniques, and the ability to convert metabolic energy into external power and velocity (i.e. efficiency or work economy) [5, 6], is of high importance for skiing performance. In modern cross-country skiing the capability to generate forward propulsion by use of the upper body has become increasingly important [11-13]. To date, little is known about how specific extensive upper body training may influence endurance performance, aerobic capacity and efficiency in cross-country skiing.

In competitive classical-style cross-country skiing, diagonal stride (DIA) and double poling (DP) are considered the most significant sub-techniques [1, 2, 14]. DIA, a technique used on moderate to steep uphill slopes, is employed by exerting force through the skis (leg push-off) and poles (arm push-off) in a coordinated pattern, in which the push-off of one arm is performed along with the push-off of the contralateral leg. DP, a technique mainly used on flat terrain, is performed with symmetrical and synchronous movements of both poles, the propulsive action of which is improved by a substantial trunk flexion while the legs' contribution is minimal [1, 2, 14, 15].

The developments in cross-country skiing over the last decades, with the introduction of sprint skiing and mass start races, in addition to more effective training, modifications of skiing techniques, better track preparation and more functional equipment, have contributed to higher race velocity and more use of the DP technique during classical races [4, 16]. Consequently, physiological determinants such as muscular strength and power of arm and trunk, as well as upper body endurance capacity, have become increasingly important for skiing efficiency and performance [4, 17-23]. Nowadays, DP is employed in parts of the tracks where earlier DIA was preferred [11, 16]. This is beneficial since DP is shown to be a more economical high speed technique with superior force effectiveness [2, 24]. As classical mass start and sprint races usually are decided in the final part, skiers with an effective DP technique have a fundamental benefit [25]. Holmberg et al [9] demonstrated that VO_{2max} during DIA was 14 % higher than VO_{2peak} in DP, whereas Fabre et al [26] found no significant differences between VO_{2peak} for the two exercise modes; both studies examined international level skiers. Peak values of heart rate, blood lactate concentration and ventilation have been found to be greater in DIA [26, 27]. These findings can be explained by a greater part of active muscles involved during DIA (upper and lower limbs acting together to propel the skier forward), although Holmberg et al [15] revealed the important contribution of the legs to DP performance in elite skiers.

The ability to efficiently convert metabolic energy into external power and velocity (i.e. mechanical efficiency) represents a key factor for endurance performance [5, 28]. Efficiency has been expressed differently within endurance sports, often divided into gross efficiency or work economy. Gross efficiency is the derivative of the ratio between work rate and total metabolic rate, expressed as a percentage [5]. Work economy is determined by measuring the steady-state oxygen uptake and the respiratory exchange ratio (RER) without knowing the work rate at a set submaximal velocity [29-31]. Although a considerable number of studies have been done on work economy in cross-country skiing [18, 27, 32-38], limited research has investigated the effects on work economy in conjunction with kinematical and performance variables following extensive specific upper body training.

Sandbakk et al [5] demonstrated higher efficiency in world-class compared to national-level cross-country skiers employing the skating G3 technique at given submaximal velocities. World-class level skiers tended to use longer cycle length (CL) and lower cycle rate (CR) due to more effective kick and pole pushes (i.e. technique factors), which possibly may be attributed to specific strength and power training [5, 16, 39, 40]. Movement characteristics were additionally investigated by Stöggl et al [40] who demonstrated that faster skiers produced greater CL with similar CR employing various skiing techniques. Moreover, the ability to generate longer gliding distances per cycle (i.e. longer CLs) at lower or similar CRs during different techniques has been demonstrated as one of the main factors to discriminate between faster and slower cross-country skiers [11, 13, 15, 39-42]. A high power output in the activated muscles is significant for the generation of long CL because of the limited time available to transfer propulsive forces [11, 16, 43, 44]. Longer recovery times for the upper and lower body may have a positive influence on blood flow and muscle recovery, which have been suggested as prerequisites for an efficient skiing technique [11, 16]. Since specific strength and power training have been attributed to enhance the ability to produce force through more effective kick and poles pushes and thereby increase CL, more emphasis has to be put on such training, especially for the upper body [5, 39, 40]. How extensive ski-specific upper body training may influence CL (i.e. work per cycle) and thereby skiing work economy and performance is, however, not yet examined longitudinally.

The aforementioned developments in competitive cross-country skiing have stressed the importance of upper body training, with current skiing techniques involving a considerable poling component relying greatly on the arms and the trunk for power generation [45]. Upper body training has been shown to increase the ratio between lower and upper body VO_{2peak}, so in elite cross-country skiers the ratio has increased from 0.7 in the 1960s to above 0.9 at the present [22]. Further, high correlations (ranging from 0.60 to 0.89) between upper body endurance capacity (VO_{2peak}) and race performance have been observed [15, 21, 22]. More recently, Fabre et al [26] found elite skiers to reach 95% of their VO_{2peak} in DIA when testing them in DP, further supporting the significance of high upper body endurance capacity among cross-country skiers. However, Alsobrook et al [46] found that measures of upper body power during simulated DP correlated even better with race performance than VO_{2peak} in the same exercise mode among well-trained skiers. Numerous studies have identified upper body power as an important predictor of competitive cross-country skiing performance [18, 20, 45-49]. Strength and power become decisive when a majority of the propulsive forces are applied through the poles [47]. Muscle power factors in endurance events are related to the ability of the neuromuscular system to rapidly produce force and power when acidity and/or oxygen uptake are high [22, 50, 51]. Studies investigating maximal strength training have suggested that an improved rate of force production during DP may result in improved work economy and an increase in time to exhaustion while DP on an ergometer [32, 35, 52]. In addition to cardiovascular abilities, limitations to modern cross-country skiing performance may be influenced by other dynamical system factors, including neuromuscular characteristics. Therefore, skiers have been forced to put more emphasis on specific upper body training stimulating neuromuscular and anaerobic factors to perform highly in modern cross-country skiing [45].

Recently, high-intensity sprint interval training (SIT; repeated ≤30-s ‘‘all-out’’ efforts) in running and cycling has shown to be an effective means for athletic endurance performance, since SIT has shown to improve both neuromuscular function and cardiorespiratory determinants in an efficient manner [53, 54]. It is interesting that SIT may induce similar or larger improvements in cardiorespiratory fitness and skeletal muscle oxidative capacity as continuous endurance training (CET) [55-57]. Apparently, the repeated SIT bouts influence many of the physiological/biochemical systems used in aerobic efforts [58, 59], such as increased maximal activities of mitochondrial enzymes [60-62], maximal oxygen uptake (VO_{2max}) [63], time to exhaustion [62, 64], and decreased glycogen utilization and lactate accumulation during identical work [64-66]. SIT may additionally be more effective than CET in improving anaerobic performance (i.e. alterations in glycolytic enzymes, muscle buffering and ionic regulation) and neuromuscular/musculoskeletal factors (i.e. potential neural adjustment and changes in force-generating capacity) [54, 63, 64, 67]. To date, limited research is available regarding the effects of SIT during upper body exercise.

To the best of our knowledge, the study by Nilsson et al [68] is the only one that has examined the effects of ski-specific upper body SIT, using a DP ergometer, on upper body power output and selected physiological and biomechanical variables in cross-country skiing. This 6-week study found that 20-s sprint type DP intervals were effective at increasing power output in a 30-s test, work economy at sub-maximal velocities, and power output in a 6-min test among well-trained cross-country skiers. Thus, SIT appears to be a particularly efficient method in enhancing upper body capabilities, and data might also indicate that an ability to produce technique-specific power at high velocities may relate to efficiency at sub-maximal speeds [5]. However, short DP intervals are not necessarily superior to other training forms in improving ski-specific upper body capacity. In the aforementioned study by Nilsson et al [68], longer DP intervals (180-s) were also found to improve the same measures of upper body power, as well as VO_{2peak} and blood lactate concentration during DP at a sub-maximal intensity. Performance measures were not evaluated in this study, so it is unclear which training regimen might result in larger performance gains. Long duration, low intensity workouts using only the DP technique are another popular method of ski-specific upper body training [46]. Terzis et al [49] investigated this training regime in well-trained cross country skiers for 20-weeks, and found a substantial improvement in performance in a 10 km classical time-trial due to induced morphological and metabolic adaptations in the specific upper body musculature. However, it has been revealed that not only the duration of the exercise but also the intensity may be a critical factor for significant adaptations in upper body muscles [49]. To date, studies comparing the effects of upper body SIT with CET training on performance and related physiological and kinematical variables in cross-country skiing are lacking, even though anecdotal evidence suggests that both training regimes are effective in increasing specific upper body capacity [46].

It has been demonstrated that gender differences in endurance performance and peak aerobic capacity among cross-country skiers become more pronounced as the contribution of upper-body propulsion (poling) increases [69]. The relative gender differences in performance associated with the DP, G3-skating, DIA and running, from solely poling in DP to no poling in running, were approximately 20%, 17%, 14% and 12% in peak velocity, and 67%, 62%, 58%, and 54% in absolute work rates. These gender differences were associated with higher VO_{2peak} (DP) both in absolute values and relative to VO_{2max} (running) in the male skiers. However, CL (i.e. work per cycle) was demonstrated to be the main differentiating factor in DP performance by male and female skiers [69]. This may indicates that female skiers still have a great potential to develop their upper body endurance-, strength – and power capacity, and in turn their poling efficiency and performance. Whether female skiers have a potential to improve their skiing performance by more emphasis on specific upper body training remains to be determined.

To the best of our knowledge, no studies to date have compared the effects of upper body SIT with CET on endurance performance, aerobic capacity and work economy in female cross-country skiers. Therefore, the purpose of the present study was to compare the effects of upper body SIT with CET in improving endurance performance, peak aerobic capacity, work economy and kinematics during incremental DP and DIA treadmill roller skiing tests among highly trained female junior cross-country skiers. Additionally, maximal upper body strength (1RM) and power of the skiers was measured. It was hypothesized that upper body SIT would be more effective than CET in improving maximal upper body strength and power and thereby lead to longer CL, and improved work economy and endurance performance during classical roller skiing.

2.0 METHODS

2.1 Experimental Approach to the Problem

To test the hypothesis that upper body sprint interval training (SIT) would be more effective than continuous endurance training (CET) in improving endurance performance, work economy and kinematics during classical roller skiing, an 8-week intervention training study was accomplished. One group added two weekly sessions of six to eight 30-s upper body sprint intervals (SIG, n=8) either using roller board in a kneeling position or by DP on roller skis at maximal effort. The other group which served as a control group (CG, n=9) added a weekly session of 45-75min of continuous low-intensity DP on roller skis. Before and after the intervention, the subjects were tested for peak velocity, peak aerobic capacity, work economy and kinematics during incremental DP and DIA treadmill roller skiing tests. Additionally, maximal upper body strength (1RM) and power in a poling specific strength exercise was measured.

2.2 Subjects

Initially, 21 highly-trained female junior cross country-skiers volunteered to participate in the study. Throughout the study period, four subjects dropped-out or were excluded due to illness or insufficient compliance to training, thus in total 17 subjects were included for the statistical analyses (**Figure 1**). The subjects were students at two Norwegian high schools with a specialized program for cross-country skiing. All subjects had trained and competed regularly in the sport of cross-country skiing for > 3 years. The skiers at one of the schools were allocated to SIG (n=8), whereas the skiers at the other school were designated to CG (n=9). The subjects' baseline physiological characteristics and anthropometrics, as well as training hours for the last season are shown in **Table 1**. There were no significant differences between groups in these variables at baseline. The study protocols and testing procedures were approved by the Regional Ethics Committee, Trondheim, Norway. All subjects were fully acquainted with the nature of the study and informed about the experimental procedure before signing written informed consent to participate. It was stated explicitly that the subjects could withdraw from the study at any point without given reason for doing so. Five of the subjects were below 18 years old and, consequently, one of their parents provided parental consent for participation in the study.

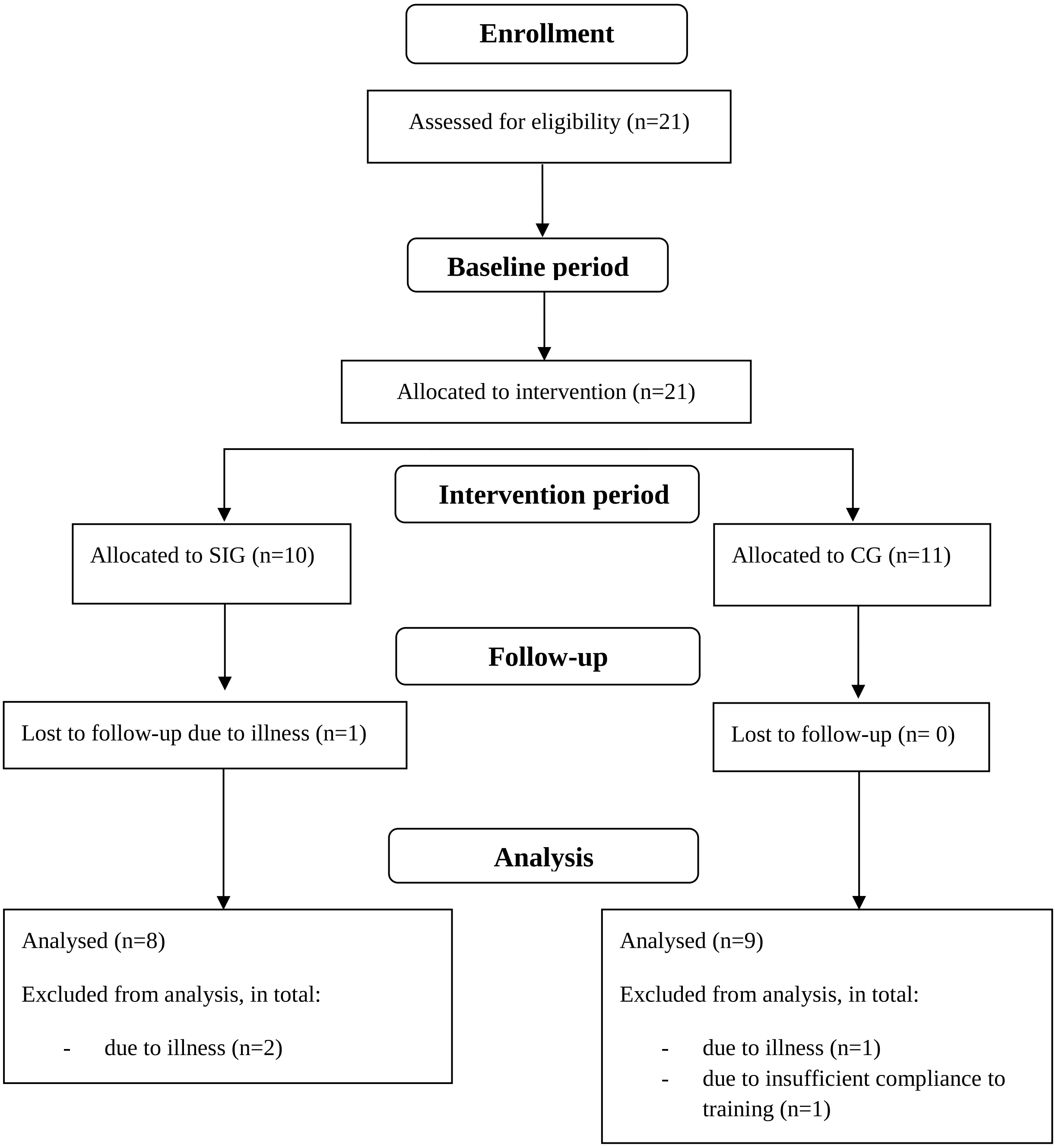

Figure 1. Flow chart of subjects throughout the study period

Table 1. Baseline physiological characteristics and anthropometrics and training hours from last season of 17 highly trained female cross-country skiers included in the analysis from this study

Variables	SIG (n=8)	CG (n=9)
	Mean±SD	Mean±SD
Age (yrs)	18.3±0.8	17.9±0.9
Body height (cm)	166.5±4.1	166.3±6.6
Body mass (kg)	60.2±6.4	60.5±8.1
VO_{2peak} double poling ($L \cdot min^{-1}$)	2.6±4.0	2.9±0.4
VO_{2peak} double poling ($ml \cdot kg^{-1} \cdot min^{-1}$)	49.8±2.8	48.1±4.9
VO_{2max} diagonal stride ($L \cdot min^{-1}$)	3.4±0.4	3.2±0.4
VO_{2max} diagonal stride ($ml \cdot kg^{-1} \cdot min^{-1}$)	56.1±2.9	53.8±4.7
Training last season (hours)	507±123	502±65

SIG, sprint interval training group; CG, control group; $VO_{2peak/max}$, peak/maximal oxygen uptake during treadmill classical roller skiing.

2.3 Procedures

The investigation took place from June 2014 to November 2014 (**Figure 2**). In June, all subjects were tested for initial physical fitness level and familiarized to test procedures and apparatus. The study comprised an 8-week baseline period (July-August), during which the subjects` training was monitored and the strength training regime standardized. All subjects were familiarized to the test exercises and the intervention training before the start of the study. This ensured that the same basic training pattern was followed during the subsequent 8-week intervention training period, which was carried out in the autumn during the early competition preparatory phase (September-October). The subjects were tested before and after the intervention training period using an identical 2-day measurement protocol for each subject (with at least 1 day to maximal 6 days between). A 2-day standardized tapering period before the testing days were performed. The pre-testing was conducted the last two weeks of August and the post-tests during the last week of October and the first week of November.

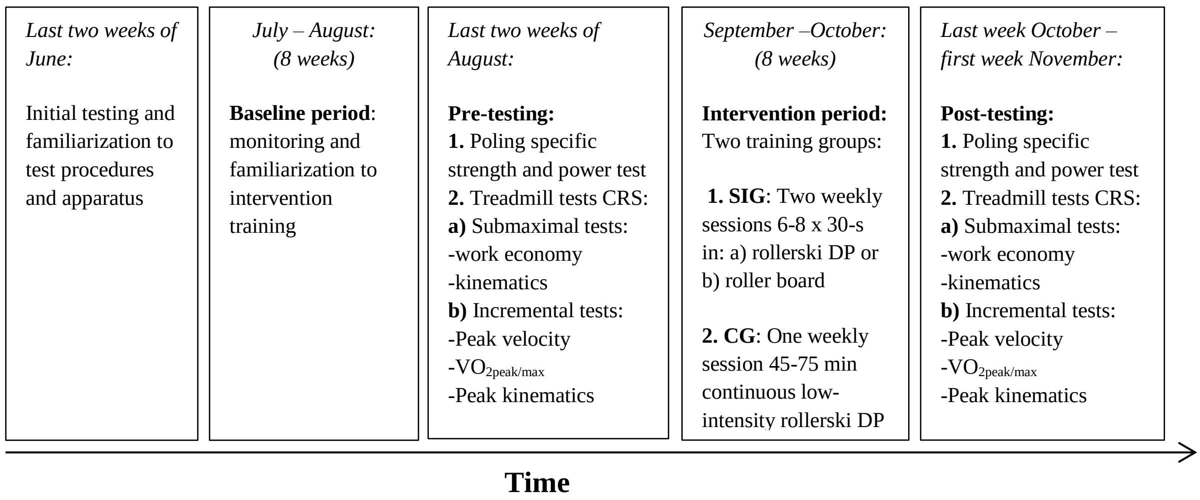

Figure 2. Schematic description of the study procedures. CRS, classical roller skiing; $VO_{2peak/max}$, peak/maximal oxygen; SIG, sprint interval training group; CG, control group; DP, double poling.

2.3.1 Pre experimental procedures

Preceding the study, all subjects attended a laboratory familiarization visit to introduce the testing and training procedures and to ensure that any learning effects was minimal between pre- and post-test. The subjects completed three submaximal stages of 5-min bouts at increasing treadmill speeds in both DP (3% incline) and DIA (12% incline), with the two techniques in an alternating sequence (see the test protocol section under submaximal test for details). As no randomization procedures were used, it was essential to evaluate each skier's initial physical fitness level, in addition to determine the intended workload for the submaximal stages for pre- and post-tests. The first stage was performed at a velocity corresponding to ~65% of their HR_{max}, which increased by 2 km h^{-1} in DP and 1 km h^{-1} in DIA for each stage. The same cardiorespiratory and blood analysis equipment was used as in the experimental study (see the test protocol section for details).

2.3.2 Training intervention

The subjects in SIG added two weekly sessions of six to eight 30-s upper-body sprint intervals of maximum sustainable effort (isoeffort) separated by 2-3 min active rest (i.e. 15-25 min total work duration per session). The SIT were performed in two different modes each week; one weekly interval-session performed while DP roller skiing in uphill sections, and the other weekly interval-session on a roller board in a kneeling position (**Figure 3**). These two poling modes were conducted for the purpose of facilitating variation in the training stimuli. DP imitation (DPI) on the roller board has been investigated for its biomechanical validity and has showed high similarities to skiing DP [70]. Each session included at least 20 min warm-up (~65% of individual HR_{max}). The SIG progressively increased the number of intervals from six to eight throughout the intervention period. The subjects started with six sprint intervals during the first two training weeks, increased to seven intervals in the subsequent three weeks and to eight intervals the last three weeks. To facilitate sufficient resistance (high power output) in the roller board sessions throughout the period, the angle of the ramp was increased stepwise according to the athletes' physical progression. The subjects had to complete at least 12 (75%) out of 16 SIT-sessions to be included for the statistical analyses.

The subjects in CG added a weekly session with 45-75 min of continuous low-intensity DP on roller skis (60-81% of HR_{max}). Training progression was accomplished by increasing the DP time from 45-min the first two training weeks, to 55-min in week 3-4, 65-min in week 5-6, and to 75-min the last two training weeks. These sessions were often incorporated in a 1.5-2 hour low-intensity classical roller skiing training. To be included for the statistical analyses, the subjects had to complete at least 360 min (75%) out of 480 min in DP time. Besides the SIT and CET sessions, the subjects maintained their baseline training during the intervention period. Each training group was followed up weekly by the investigators and educated coaches during the intervention training period. Training plans, a training diary, and written instructions about how to record training were provided and explained to the subjects. Emphasize was placed at close and similar supervision and monitoring of both groups throughout the intervention period.

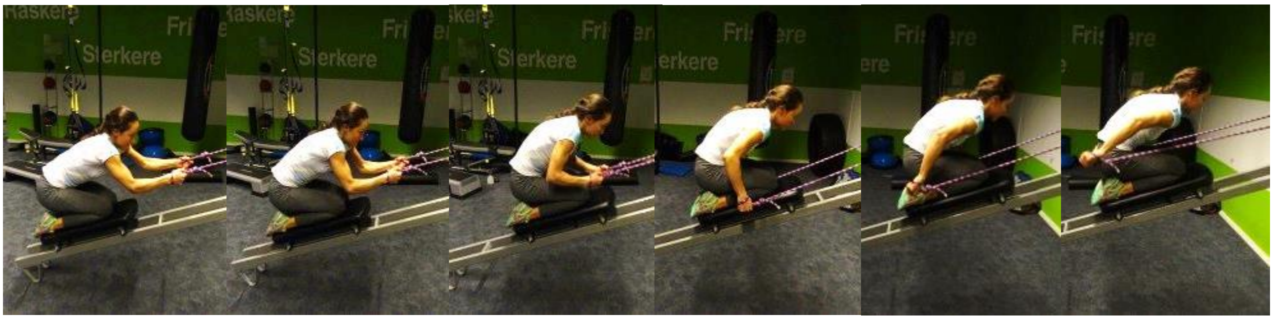

Figure 3. Roller board exercise in kneeling position

2.4 Instruments and materials

2.4.1 Strength and power tests

The poling specific strength and power exercise test was performed while sitting on an upraised adjustable bench placed in front of a multi cable apparatus (Beach Mountain AS, Norway) with custom made grips and straps attached to the cord (**Figure 4**). The back rest was at a ~120º angle with the seat. The skier sat on the bench with a ~90º angle at the knees and was strapped around the hips to isolate the upper body. The friction in the pulldown apparatus, as measured with the Noraxon force cell, did not change with increasing weight. For the investigation of velocity and force for further analysis of average power in Watts, it was used a linear encoder (Muscle Lab Power, Ergotest Innovation AS, Porsgrunn, Norway). The data obtained was processed with a computer software program (MuscleLab 3010E, software version 7.17; Ergotest Technology AS). The average power was calculated from the formula $P = F \cdot v$, where F is force (N) and v is velocity ($min \cdot s^{-1}$).

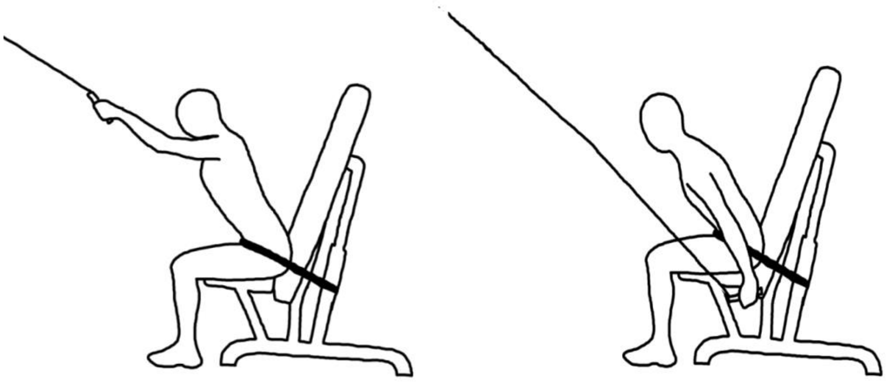

Figure 4. Poling specific strength and power exercise. 1: Start position 2: End position

2.4.2 Treadmill tests

Gas exchange values were measured by open-circuit indirect calorimetry with an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany), which has previously been validated [71]. Prior to each test day, VO_2 and VCO_2 gas analyzers were calibrated using a high-precision composition of gases (16.00±0.04% O_2 and 5.00±0.1% CO_2, Riessner-Gase GmbH & Co, Lichtenfels, Germany) and the inspiratory flow meter was calibrated with a 3-L volume syringe (Hans Rudolph Inc., Kansas City, MO). Heart rate (HR) was continuously measured during all tests using a Suunto t6c HR monitor (Suunto Oy, Vantaa, Finland) with 5-s registration intervals. Peak heart rate (HR_{peak}) was defined as the highest HR recorded during the maximal tests. Blood lactate concentration (BLa) was determined from a 5 μL blood sample taken from the fingertip and analyzed for BLa by a Lactate Pro LT-1710t (ArkRay Inc., Kyoto, Japan) according to the manufacturer’s instructions. This instrument has been found reliable for use in athletic testing [72, 73]. Samples were taken directly after each submaximal test, as well as one min after each maximal test. Cardiorespiratory variables were averaged from the 3rd to the 4th minute of each submaximal stage. Body mass was measured on the Kistler force plate (Kistler 9286AA, Kistler instrument Corp., Winterthur, Switzerland) and body height self-reported by the subjects. The rollerski tests were performed on a 2.5 x

3.5-m motor-driven treadmill (Rodby, Sodertalje, Sweden). The surface of the treadmill belt was covered with non-slip rubber that allowed the skiers to use their own poles (pole length: 83.3±0.6% of body height) with special carbide tips put on the bottom ends of the poles. The subjects were secured with a safety harness during the treadmill testing. To exclude possible variations in rolling resistance, all skiers used the same pair of Pro-ski classic roller skis with standard wheels (C2 Classic Pro-Ski, Sterners, Nyhammar, Sweden) and the same Rottefella binding system (Rottefella AS, Klokkartstua, Norway). The roller skis were pre-warmed before each test through 10 min of roller skiing on the treadmill. Both, the treadmill`s inclination and speed were calibrated using the Qualisys Pro Reflex system and the Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). For the determination of kinematic cycle characteristics during each test in each technique, a Sony video camera (Sony Handycam DCR-VX2000E, Sony Inc., Tokyo, Japan) was fixed on the side of the treadmill, enabling full view of the subjects and the movement range of the poles. The video recordings were analyzed utilizing the Dartfish Pro 4.5 program (Dartfish Ltd, Fribourg, Switzerland).

2.5 Test protocols, measurements and data collection

On the first test day subjects were investigated for their maximal upper body strength (1RM) and average power at 40% 1RM (P_{40}) in the poling specific exercise.

The second test day (**Figure 5)** (>48 hours between the test days) the subjects completed (1) three 5-min submaximal stages in both DP and DIA roller skiing, with the two techniques in an alternating sequence, for determination of work economy (measured as submaximal VO_2), kinematics (CR and CL) and physiological responses (VO_2, VE, RER, HR and BLa). After 10-min of active rest, (2) an incremental test to exhaustion in DP was performed to determine peak aerobic capacity (VO_{2peak}), treadmill performance (peak velocity; v_{peak}) and peak kinematics (CL_{peak} and CR_{peak}). After ~20 min of recovery, which of the last 3-5 min were low-intensity DIA, (3) an incremental test to exhaustion in DIA was performed to determine VO_{2max}, v_{peak} and peak kinematics (CL_{peak} and CR_{peak}).

All tests were performed under approximately similar environmental conditions (18-21˚C) with a fan ensuring circulating air. Testing at pre- and post-intervention was conducted at the same time of day (±2 hrs) to avoid influence of circadian rhythm. The subjects were instructed to perform the last SIT session three days before the tests and to refrain from all types of intense exercise the day proceeding each of the two test days. It was stated explicitly to the subjects that they should do the same preparations before every test.

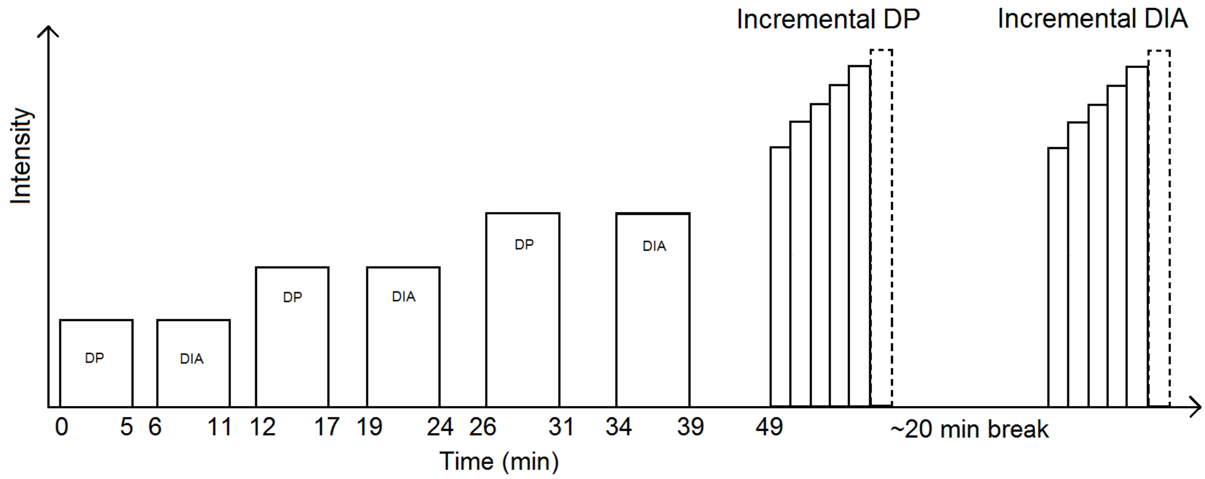

Figure 5. Illustration of the test protocol for the treadmill tests including submaximal tests and incremental tests to exhaustion in double poling (DP) and diagonal stride (DIA) technique.

2.5.1 Strength and power tests

Prior to the strength and power test, each subjects warmed up for 10-min by running on a treadmill at a low intensity (~65% of HR_{max}) and then performed four sets of exercise-specific warm up with gradually increasing load: two sets of ten repetitions at 40%, five repetitions at 60% and three repetitions at 80% of the expected 1RM [74]. The subjects were holding a handlebar specifically designed to imitate the grip on poles in cross country skiing, starting with the arms completely extended at shoulder level. During the last part of the pull-down the elbow joint should be extended more than 90° to be accepted. The criteria for the poling specific test being accepted was that the processus styloideus ulnae should reach the trochanter major at the hip. The first attempt was performed with a load of 2.5kg below the expected 1RM. After each successful attempt, the load was increased by 1 to 5 kg until the subject failed to lift the load correctly, after two to three consecutive attempts. The rest period between each attempt was 2 min. Finally, the average power at 40% 1RM in one pull-down was measured. Two trials were performed and analyzed for average power, with two minutes of rest in between, with best attempt used for further analyses. The subjects were instructed to produce maximal power during both trials. All strength and power tests were supervised by the same investigator and conducted on the same equipment with identical equipment positioning for each subject.

2.5.2 Treadmill tests

Submaximal tests

The submaximal treadmill tests started with a standardized low-intensity 10-min warm up, consisting of 5-min DP and 5-min DIA at ~65% of the individual HR_{max}. Thereafter, physiological and kinematical responses in connection to submaximal exertion were monitored during six 5-min bouts in DP and DIA, with the two techniques in an alternating sequence, conducted at low to moderate exercise intensity. The breaks between the submaximal stages were 1-, 2- and 3-min. The incline of the treadmill was set at 3% for DP and 12% for DIA. The velocity of the first submaximal stage in each technique was corresponding to ~65 % of their HR_{max} (6-8 km h^{-1} in DP and 5-6 km h^{-1} in DIA), which increased by 2 km h^{-1} in DP and 1 km h^{-1} in DIA for each stage. Oxygen uptake (VO_2) during the submaximal tests, at the velocity of 10 km h^{-1} (V10) in DP and 7 km h^{-1} (V7) in DIA, during which all subjects reached an aerobic steady-state condition, was used in the calculation of work economy. The BLa and the rate of perceived exertion (RPE) using a 6-20 Borg scale [75] were assessed immediately after each test. Kinematics (CL and CR) were examined during the final minute at standardized submaximal velocity at V10 in DP and V7 in DIA, respectively. The average VO_2, VE, RER and HR from the 3rd to the 4th minute was measured during each 5-min bout.

Incremental tests to exhaustion

After the submaximal tests, the subjects had 10 min of recovery before (1) completing an incremental test to exhaustion in DP, followed by ~20 min recovery period (in which the last 3-5 min was easy DIA) and then (2) completed an incremental test to exhaustion in DIA. The rest phase between the incremental tests was based on recovery time between final heats in cross-country sprint skiing competitions, and found long enough to prevent accumulation of fatigue [76].

$VO_{2peak/max}$, treadmill performance (v_{peak}) and peak kinematics (CL_{peak} and CR_{peak}) were examined using incremental increases in the velocity of the treadmill maintained at a constant incline (at 3% in DP and 12% in DIA). The incremental test in DP was performed with an initial velocity of 12 km h^{-1}. The velocity was increased by 2 km h^{-1} after the first minute up to 14 km h^{-1}, and thereafter increased by 1 km h^{-1} every minute until exhaustion. During DIA, the initial velocity of 8 km h^{-1} was increased 1 km h^{-1} every minute until volitional exhaustion. The inclines and velocities in the roller ski tests were chosen on the basis of where these techniques are used during races and experiences from pilot testing and earlier studies involving these types of tests [77, 78]. Exhaustion was defined as the time-point at which the skiers were no longer able to keep the forefoot in front of a marker on the treadmills and determined the individual treadmill performance (peak velocity; v_{peak}). The test was designed to last approximately 4-8 min. The test was considered to be a maximal effort if the following 3 criteria were met: (a) a plateau in VO_2 with increasing exercise intensity, (b) a RER-value >1.15 and a RPE >18, and (c) BLa > 8 $mmol \cdot L^{-1}$ [79]. VO_2, HR, RER and VE were measured continuously, and the average of the three highest 10-second consecutive measurements determined peak values. The BLa_{peak} was measured one min after completion of the test, whereas RPE was given immediately after completion. Peak velocity (v_{peak}) was calculated as $v_f + [(t \cdot T^{-1}) \cdot v_d]$, where v_f was the velocity associated with the final workload, t the duration for which this maximal workload was maintained, T the duration of each individual level of workload, and v_d the difference in the velocities at which the final two workloads were performed [11, 77]. Peak kinematics (CR_{peak} and CL_{peak}) were measured during the last completed workload. One DP cycle was defined as the period from the start of the pole ground contact to the start of the subsequent pole ground contact. One DIA cycle was defined as the period between the start of the pole-out of the left pole to the subsequent pole ground contact of the same pole. All data were averaged over ten cycles. The CL was calculated as the velocity multiplied by the cycle time (CT) and the CR as the reciprocal of CT. These kinematical variables were assessed both during the final minute at the set submaximal speed of V10 (DP) and V7 (DIA), and during the final 30-s workload in both incremental tests to exhaustion in DP and DIA.

2.6 Training history survey

Training data from July – November was recorded based on the skiers' own online training diaries (Olympiatoppens treningsdagbok, Lyymp AS, Norway), that each subject voluntarily accepted the research team to access. This self-reporting of training is well known among cross-country skiers in Norway and is found valid according to monitored HR [80]. Intensity and type of exercise, including endurance, speed and strength training was registered. Endurance training intensity was categorized into three intensity zones, according to a modification of the Norwegian Olympic system's intensity scale [81]: (1) low intensity (INT1; 1.5–2.5 mmol L^{-1} BLa, 60–81% of HR_{max}), (2) moderate intensity (INT2; 2.5–4 mmol L^{-1} BLa, 82–87% of HR_{max}), and (3) high intensity (INT3; >4 mmol L^{-1} BLa, >88% of HR_{max}). Strength training was categorized into maximal strength training (MST) (≥85% 1RM, 4-5 repetition, 3-5 set with >2min rest between) and general strength training (GST) (<60% 1RM, 12-18 repetitions, 3-4 set with 1-1.5 min rest between). Speed training (speed) was another category (<10 second bouts of maximal effort) as was anaerobic training (anaerobic) (30-s bouts of maximal effort). In addition, there were the following exercise mode categories; roller ski classical (RSC), roller ski skate (RSS) and running (RUN). Skiing was merged with roller skiing. The online diary allowed the investigators to continuously follow the training performed by the participants through the intervention period, with the possibility of giving guidance to standardize the trainings as far as possible.

2.7 Training data

Weekly volume distribution of training intensity and mode during the intervention period in SIG and CG are displayed in **Table 2**. The compliance of the schedule intervention training was 83% in SIG and 77% in CG. The groups did not differ significantly in either volume of training mode or intensity during the baseline period or during the previous season. During the intervention period, significant between-group differences in training data were more anaerobic and speed training in SIG (both $p<0.001$), while CG trained more GST and INT2 (both $p<0.05$). From baseline to the intervention period, only anaerobic training was significantly increased in SIG compared to CG ($p<0.001$).

Table 2. Weekly endurance, strength, speed training and different exercise modes during the 8-week intervention training period in 17 highly trained female cross country skiers (hh:mm).

	SIG (n=8)	CG (n=9)
	Mean±SD	Mean±SD
INT1	9:48±1:57	10:10±2:54
INT2	0:25±0:08	0:37±0:14$^{\#}$
INT3	0:38±0:07	0:36±0:10
Anaerobic	0:30±0:11$^{\#\#**}$	0:00±0:01
MST	0:32±0:09	0:45±0:13
GST	0:43±0:24	1:08±0:19$^{\#}$
Speed	0:22±0:04$^{\#\#}$	0:08 ± 0:07
RSC	2:58±0:23	3:04±0:52
RSS	2:16±0:33	1:42±0:52
RUN	4:50±1:34	4:35±2:13
Other	0:35±0:30	0:20±0:15
TOTAL	13:38±2:26	13:51±3:44

SIG, sprint interval training group; CG, control group; INT1, 60-81% of HR_{max}; INT2, 82-87% of HR_{max}; INT3, 88-97% of HR_{max}; Anaerobic, all-effort bouts (30-s) separated by 2-3 min rest; MST, maximal strength training (≥85% of 1RM); 4-5 repetitions x 3-5 set separated by 2-3 min rest; GST, general strength training (<60% of 1RM); 12-18 repetitions x 3-4 set separated by ~1 min rest; Speed, all-effort bouts (<10-s) separated by 2-3 min rest; RSC, roller ski classical; RSS, roller ski skating; RUN, running with or without poles ("skigang"/ "elghufs"); Other, other exercise modes (cycling, kayaking etc.). Significantly different between training groups during intervention period: $^{\#}p<0.05$,

$^{\#\#}$p<0.001. Significant difference in increase from baseline to intervention period between groups: **p<0.001.

2.8 Statistical analysis

All data were checked for normality by calculating *Z*-scores for skewness and kurtosis (criteria *Z*-value = -1.96<Z<1.96). Data are presented as mean±standard deviations (SD). Possible significant differences between groups at pre-test were checked by using an independent sample t-test procedure. Pre- to posttest changes within groups were tested by the paired samples t-test procedure. To investigate between group effects, univariate ANOVA, with the gain score (posttest-pretest) as the dependent variable, was performed. The rationale for using univariate ANOVA was to supplement the analyses with effect size (partial eta square, $p\eta^2$) and the observed power (1-β). Due to between group differences at pre-test in one case, it was applicable to perform an ANCOVA with pretest score as a covariate variable and gain score as the dependent variable. For variables that did not meet the requirements for normality, within and between group effects were investigated by Wilcoxon Test and Man Whitney U Test procedures. Statistical significance was set at an alpha level < 0.05. All statistical analyses were performed as two-tailed tests. Repeated measurements of the physiological and kinematical variables on the treadmill demonstrated intraclass correlation coefficients > 0.95. All statistical analyses were performed using the SPSS 21.0 Software for Windows (SPSS, Inc., Chicago, IL) and Office Excel 2010 (Microsoft Corporation, Redmond, WA).

3.0 RESULTS

3.1 Strength and power tests

There were no significant changes in body mass from pre to post-test, neither within groups nor between groups (all P<0.05).

Pre- and post-test scores for 1RM and P_{40} are shown in **Figure 6a-b** and **7a-b**, respectively.

The 1RM improved by 17.6±7.6% (7.9±3.0 kg; P<0.001) from pre- to post-test for SIG and by 9.8±4.9% (4.7±2.7 kg; P=0.001) for CG. This increase was greater in SIG compared to CG (+3.2±1.4 kg; $F_{1,15}$=5.4, P=0.034, η^2=0.27, 1-β=0.59).

P_{40} increased by 20.1±5.7% (34.9±11.1 W; P<0.001) from pre- to post-test in SIG and by 14.1±9.1% (22.8±13.0 W; P=0.008) in CG. SIG tended to increase P_{40} more than CG (+12.1±5.9 W; $F_{1,15}$=4.2, P=0.057, η^2=0.22, 1-β=0.49).

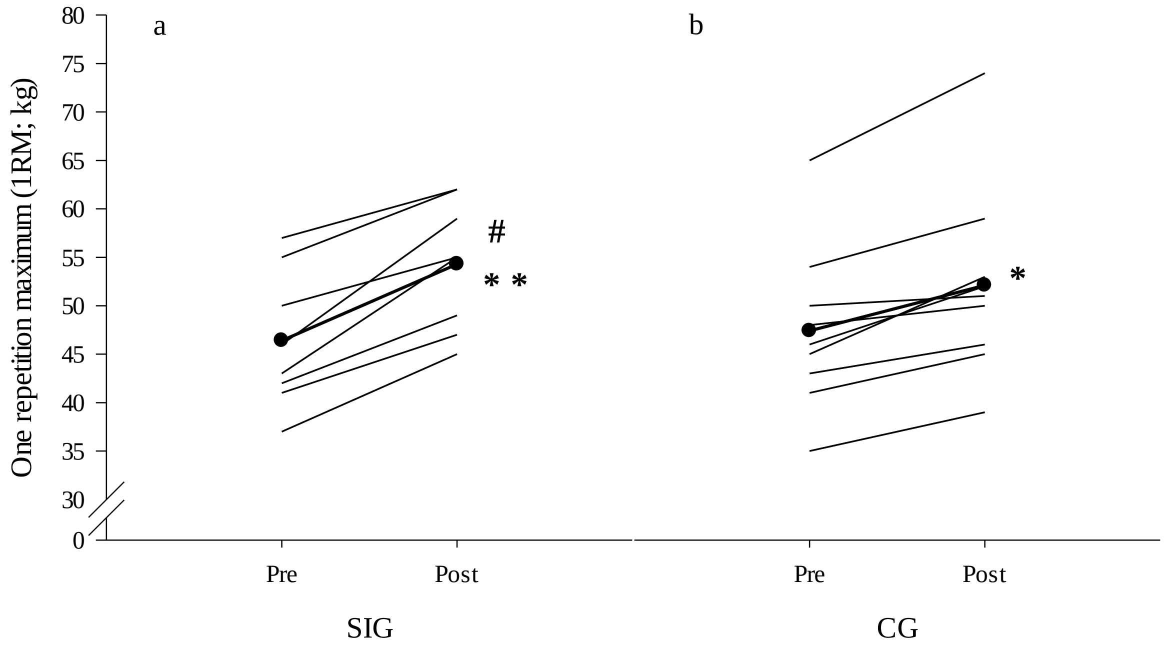

Figure 6a and b. Individual data points for one repetition maximum before (Pre) and after the intervention period (Post) for the upper body sprint interval training group (SIG) and the control group (CG). Mean values are represented by the thick line with black circles. Significant within-group changes: *P<0.05, **P<0.001; Significant different change from pre to post between groups: #P<0.05.

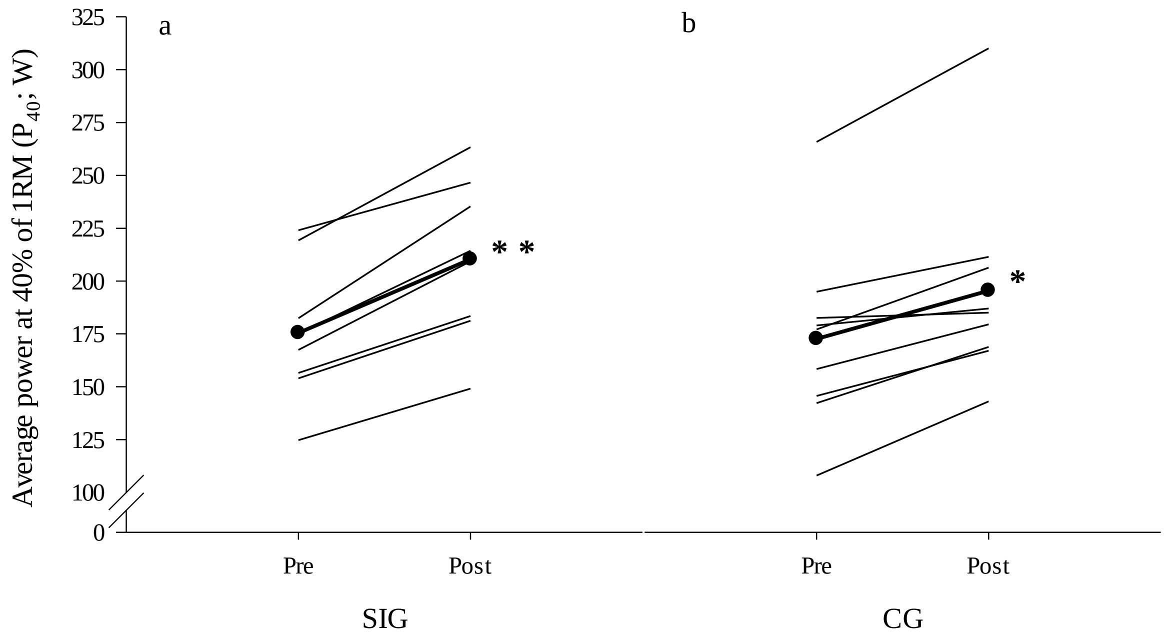

Figure 7a and b. Individual data points for average power at 40% of one repetition maximum before (Pre) and after the intervention period (Post) for the upper body sprint interval training group (SIG) and the control group (CG). Mean values are represented by the thick line with black circles. Significant within-group changes: *P<0.05, **P<0.001.

3.3 Submaximal responses

Submaximal physiological and kinematical responses at pre- and post-tests conditions in the DP technique are displayed in **Table 3**.

VO_2 in absolute terms increased by 0.11±0.10 L min^{-1} (P=0.019) from pre- to post-test for SIG, and SIG tended to increase VO_2 relative to body mass by 1.4±1.9 ml kg^{-1} min^{-1} (P=0.077). CG did not differ in these variables. SIG increased VO_2 in absolute terms and tended to increase VO_2 relative to body mass more than CG (+0.13±0.06 L min^{-1}; P=0.037 and +1.9±1.0 ml kg^{-1} min^{-1}; P=0.076). Moreover, VE increased by 4.4±3.3 L min^{-1} (P=0.008) from pre- to post-test in SIG, and SIG increased VE more than CG (+7.4±2.3 L min^{-1}; P=0.006).

RER decreased by -0.05±0.05 (P=0.014) from pre- to post-test in CG, while SIG did no differ (P>0.05). CG decreased their RER more than SIG (-0.5±0.2; P=0.031).

No other significant differences in DP were revealed, neither within nor between groups.

Table 3. Submaximal physiological and kinematical responses at pre- and post-tests conditions during double poling (DP) treadmill roller skiing (12% incline) at standardized speed (10 km h^{-1}) for 17 highly trained junior female cross-country skiers.

	SIG (n=8)		CG (n=9)		SIG vs. CG			
	Pre	Post	Pre	Post	Between-groups effects			
Variables	Mean±SD	Mean±SD	Mean±SD	Mean±SD	F-value	Sig.	$p\eta^2$	1-β
VO_2 (ml·kg^{-1}·min^{-1})	29.3±2.3	30.7±2.2	30.5±3.0	30.0±2.2	$F_{(1,15)}$=3.6	P=0.08	0.20	0.43
VO_2 (L·min^{-1})	1.77±0.27	1.88±0.22*	1.84±0.24	1.82±0.20	$F_{(1,15)}$=5.2	P=0.04#	0.26	0.57
VE (L·min^{-1})	52.8±7.3	57.1±8.6*	56.0±7.3	53.0±7.0	$F_{(1,15)}$=10.0	P=0.01#	0.40	0.84
RER	0.97±0.07	0.97±0.05	0.98±0.04	0.93±0.05*	$F_{(1,15)}$=5.6	P=0.03#	0.27	0.60
HR (bpm)	165.4±16.3	172.6±7.9	174.3±9.1	175.8±5.1	$F_{(1,15)}$=0.0	P=0.97	0.00	0.05
RPE (6-20)	11.0±2.9	10.5±3.2	12.3±2.0	12.0±2.1	[a]Z=-0.75	P=0.48	NA	NA
BLa (mmol L^{-1})	2.69±1.02	2.98±1.47	2.92±1.00	2.79±0.74	$F_{(1,15)}$=1.18	P=0.30	0.07	0.17
CR (Hz)	0.70±0.12	0.71±0.12	0.74±0.07	0.73±0.08	[a]Z=-0.53	P=0.60	NA	NA
CL (m)	4.07±0.66	4.00±0.64	3.81±0.38	3.82±0.45	[a]Z=-0.39	P=0.74	NA	NA

SIG, sprint interval training group; CG, control group; VO_2, oxygen uptake; VE, ventilation; RER, respiratory exchange ratio; HR, heart rate; RPE, rating of perceived exertion; BLa, blood lactate concentration; CR, cycle rate; CL, cycle length. Within-group differences: *P<0.05; between-group differences: #P<0.05. [a]: Based on Mann-Whitney U test (see the statistical section for details). NA: Not available due to use of Mann-Whitney U test (see the statistical section for details).

Submaximal physiological and kinematical responses at pre- and post-tests conditions in the DIA technique are displayed in **Table 4**.

In VO_2 relative to body mass the groups did differ in the pre-test value (P=0.018), SIG had a greater pre-test value than CG (+2.4 ml kg^{-1} min^{-1}). The pre-test value was added as a covariate variable.

RER decreased by -0.04±0.05 (P=0.005) from pre- to post-test in CG, while SIG did not differ (P>0.05).

No other significant differences in DIA were revealed, neither within nor between groups.

Table 4. Submaximal physiological and kinematical responses at pre- and post-tests conditions in diagonal stride (DIA) treadmill roller skiing (3% incline) at standardized speed (7 km h^{-1}) for 17 highly trained junior female cross-country skiers

	SIG (n=8)		CG (n=9)		SIG vs. CG			
	Pre	Post	Pre	Post	Between-groups effects			
Variables	Mean±SD	Mean±SD	Mean±SD	Mean±SD	F-value	Sig.	$p\eta^2$	1-β
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	44.6±2.2	44.4±2.1	42.2±1.5	42.3±1.3	[b]$F_{(1,15)}$=2.7	P=0.13	0.16	0.33
VO_2 ($L \cdot min^{-1}$)	2.69±0.27	2.71±0.19	2.55±0.32	2.57±0.30	$F_{(1.15)}$=0.01	P=0.92	0.00	0.05
VE ($L \cdot min^{-1}$)	77.9±15.0	73.3±10.5	69.4±11.1	67.4± 8.8	$F_{(1,15)}$=0.49	P=0.49	0.03	0.10
RER	0.93±0.04	0.92±0.02	0.93±0.04	0.88±0.04*	$F_{(1,15)}$=2.09	P=0.17	0.12	0.27
HR (bpm)	165.4±16.3	172.6±7.9	174.3±9.1	175.8±5.1	$F_{(1,15)}$=0.99	P=0.34	0.06	0.15
RPE (6-20)	13.8±3.3	12.5±2.6	14.2±2.1	13.6±2.1	$F_{(1,15)}$=0.42	P=0.53	0.03	0.09
BLa (mmol L^{-1})	3.35±2.11	2.89±1.18	3.39±2.10	2.36±0.84	[a]Z=-0.58	P=0.61	NA	NA
CR (Hz)	0.70±0.06	0.68±0.06	0.77±0.04	0.76±0.07	[a]Z=-0.97	P=0.96	NA	NA
CL (m)	2.79±0.26	2.87±0.25	2.54±0.13	2.56±0.24	[a]Z=0.00	P=1.00	NA	NA

SIG, sprint interval training group; CG, control group; VO_2, oxygen uptake; VE, ventilation; RER, respiratory exchange ratio; HR, heart rate; RPE, rating of perceived exertion; BLa, blood lactate concentration; CR, cycle rate; CL, cycle length. Within-group differences:*P<0.05. [a]:Based on Mann-Whitney U test (see the statistical section for details). [b]: Based on ANCOVA, with pretest score as a covariate variable, due to between group differences in pre-test NA: Not available due to use of Mann-Whitney U test (see the statistical section for details).

3.4 Maximal responses

Maximal physiological and kinematical responses at pre-and post-tests conditions in DP technique are displayed in **Table 5** and **Figure 8a-b** and **9a-b**.

Performance (peak velocity; v_{peak}) in DP improved by 4.5±3.5% (0.7±0.5 km h^{-1}; P=0.011) from pre- to post-test in CG, while SIG did not change (P>0.05). The groups did not differ from pre- to post-test in DPv_{peak} (P>0.05).

VO_{2peak} increased 9.0±6.3% (4.5±3.2 ml kg^{-1} min^{-1}; P=0.005) and 10.9±7.9% (0.3±0.2 L min^{-1}; P=0.005) from pre- to post-test in SIG, and by 5.9±6.4% (2.7±3.1 ml kg^{-1} min^{-1}; P=0.031) and 6.4±5.4% (0.2±0.2 L min^{-1}; P=0.008) in CG. The groups did not differ from pre- to post-test in VO_{2peak} (P>0.05).

HR_{peak} and BLa_{peak} increased by 2.9±2.8 beat per min (P=0.014) and by 1.5±1.8 mmol L^{-1} (P=0.036) from pre- to post-test in CG, while SIG did not differ (both P>0.05). A tendency to increased VE_{peak} occurred for SIG by 10.0±13.8 L min^{-1} (P=0.079) from pre- to post-test. The groups did not differ from pre- to post-test in these variables (both P>0.05).

No other significant differences in DP were revealed, neither within nor between groups.

Table 5. Maximal physiological and kinematical responses at pre-and post-tests conditions during double poling (DP) treadmill roller skiing (3% incline) for 17 highly trained junior female cross-country skiers

	SIG (n=8)		CG (n=9)		SIG vs. CG			
	Pre	Post	Pre	Post	Between-groups effects			
Variables	Mean±SD	Mean±SD	Mean±SD	Mean±SD	F-value	Sig.	$p\eta^2$	1-β
Peak speed (km·h^{-1})	17.7±1.2	18.1±1.2	16.9±1.5	17.6±1.4*	$F_{(1,15)}$=0.5	P=0.49	0.03	0.10
VO_2 (ml·kg^{-1}·min^{-1})	49.8±2.8	54.3±4.5*	48.1±4.9	50.8±4.1*	$F_{(1,15)}$=1.5	P=0.25	0.09	0.20
VO_2 (L·min^{-1})	3.00±0.40	3.32±0.35*	2.90±0.35	3.07±0.30*	$F_{(1,15)}$=2.4	P=0.15	0.14	0.30
VE (L·min^{-1})	118.0±16.4	128.0±15.2	108.8±15.5	111.0±11.4	$F_{(1,15)}$=1.6	P=0.23	0.10	0.22
RER	1.11±0.05	1.09±0.08	1.09±0.03	1.07±0.04	$F_{(1,15)}$=0.1	P=0.78	0.01	0.06
HR (bpm)	189.4±4.5	191.5±4.0	189.4±4.4	192.3±2.8*	$F_{(1,15)}$=0.2	P=0.67	0.01	0.07
RPE (6-20)	18.5±1.2	18.8±1.3	18.7±0.9	18.6±0.7	$F_{(1,15)}$=0.5	P=0.51	0.03	0.10
BLa (mmol L^{-1})	8.70±2.00	9.53±1.03	8.34±1.74	9.88±2.33*	$F_{(1,15)}$=0.6	P=0.46	0.04	0.11
CR (Hz)	1.05±0.15	1.11±0.12	1.16±0.11	1.19±0.15	$F_{(1,14)}$=0.3	P=0.59	0.02	0.08
CL (m)	4.82±0.60	4.61±0.65	4.05±0.48	4.19±0.81	$F_{(1,14)}$=2.4	P=0.15	0.14	0.30

SIG, sprint interval training group; CG, the control group; VO_2, oxygen uptake; VE, ventilation; RER, respiratory exchange ratio; HR, heart rate; RPE, rating of perceived exertion; BLa, blood lactate concentration; CR, cycle rate; CL, cycle length. Within-group differences: *P<0.05.

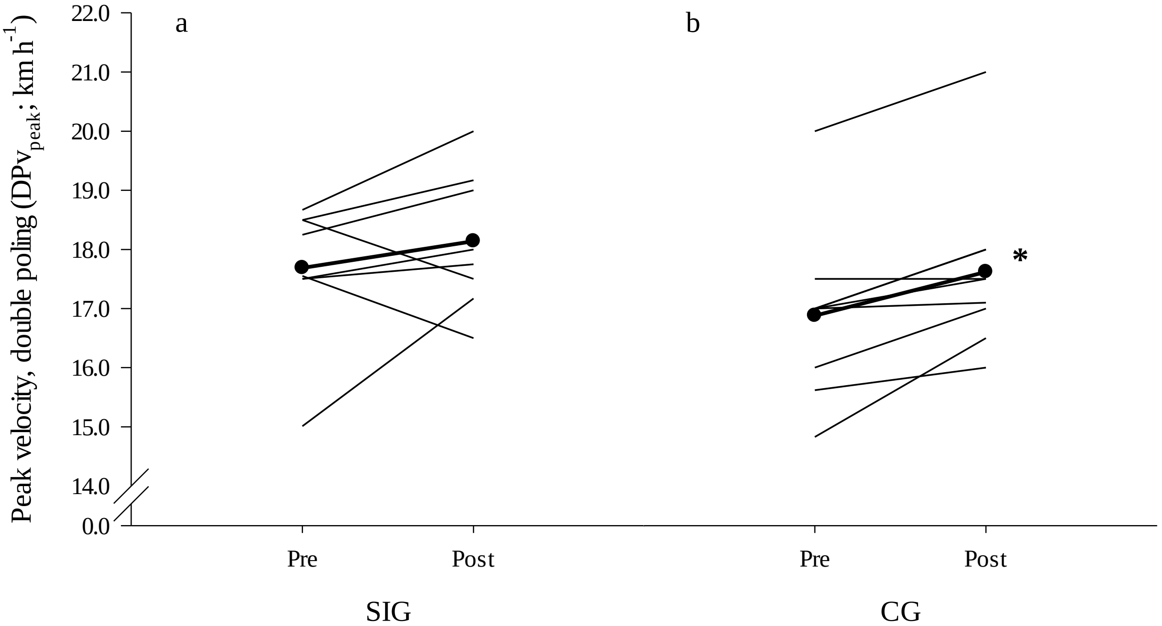

Figure 8a and b. Individual data points for peak velocity in double poling before (Pre) and after the intervention period (Post) for the upper body sprint interval training group (SIG) and the control group (CG). Mean values are represented by the thick line with black circles. Significant within-group changes: *P<0.05.

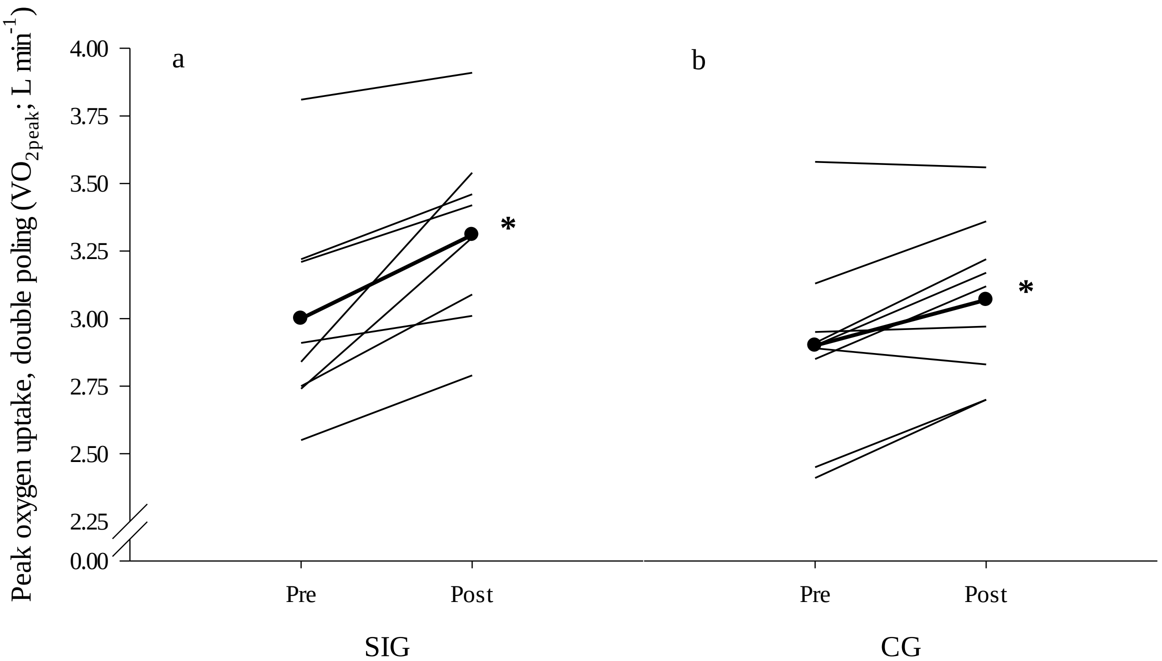

Figure 9a and b. Individual data points for peak oxygen uptake in absolute terms in double poling before (Pre) and after the intervention period (Post) for the upper body sprint interval training group (SIG) and the control group (CG). Mean values are represented by the thick line with black circles. Significant within-group changes: *P<0.05.

Maximal physiological and kinematical responses at pre-and post-tests conditions in the DIA technique are displayed in **Table 6** and **Figure 10a-b** and **11a-b**.

VO_{2max} improved by 6.9±5.3% (3.8±3.0 ml kg^{-1} min^{-1}; P=0.008) and by 8.6±6.4% (0.3±0.2 L min^{-1}; P=0.005) from pre- to post-test in SIG, while CG did not differ in these variables (all P>0.05). The increased VO_{2max} in absolute terms in SIG was greater than in CG (+0.2±0.1 L min^{-1}; P=0.033), and the same tendency occurred for VO_{2max} relatively to body mass (+2.8±1.4 ml kg^{-1} min^{-1}; P=0.065).

VE_{peak} increased by 8.0±8.7 L min^{-1} (P=0.036) from pre- to post-test in SIG, while CG did not differ (P>0.05). The groups did not differ from pre- to post-test in VE_{max} (both P>0.05).

No other significant differences in DIA were revealed, neither within nor between groups.

Table 6. Maximal physiological and kinematical responses at pre-and post-tests conditions in diagonal stride (DIA) treadmill roller skiing (12% incline) for 17 highly trained female junior cross-country skiers.

	SIG (n=8)		CG (n= 9)		SIG vs. CG			
	Pre	Post	Pre	Post	Between-groups effects			
Variables	Mean±SD	Mean±SD	Mean±SD	Mean±SD	F-value	Sig.	$p\eta^2$	1-β
Peak speed (km·h^{-1})	11.0±0.3	11.1±0.5	10.6±1.0	10.8±0.8	$F_{(1,15)}$=0.04	P=0.85	0.00	0.05
VO_2 (ml·kg^{-1}·min^{-1})	56.1±2.9	59.9±3.9*	53.8±4.7	54.8±4.4	$F_{(1,15)}$=4.0	P=0.07	0.21	0.46
VO_2 (L·min^{-1})	3.38±0.37	3.65±0.24*	3.24±0.37	3.31±0.33	$F_{(1,15)}$=5.5	P=0.03#	0.27	0.59
VE (L·min^{-1})	127.8±15.2	135.8±12.7*	113.2±14.1	117.4±9.8	$F_{(1,15)}$=0.7	P=0.4	0.05	0.13
RER	1.16±0.04	1.14±0.08	1.11±0.06	1.09±0.04	$F_{(1,15)}$=0.00	P=0.95	0.00	0.05
HR (bpm)	190.6±5.9	190.1±3.2	190.3±3.8	189.8±3.1	$F_{(1,15)}$=0.00	P=0.98	0.00	0.05
RPE (6-20)	19.6±0.7	19.4±0.7	19.3±0.5	19.2±0.8	$F_{(1,15)}$=0.12	P=0.74	0.01	0.06
BLa (mmol L^{-1})	10.88±1.97	10.78±1.64	9.41±2.26	10.31±2.94	$F_{(1,15)}$=1.5	P=0.24	0.09	0.21
CR (Hz)	0.92±0.08	0.91±0.04	0.92±0.05	0.93±0.05	$F_{(1,14}$ =0.7	P=0.43	0.04	0.12
CL (m)	3.35±0.28	3.51±0.16	3.25±0.28	3.32±0.18	$F_{(1,14)}$=0.7	P=0.41	0.05	0.12

SIG, sprint interval training group; CON, control group; VO_2, oxygen uptake; VE, ventilation; RER, respiratory exchange ratio; HR, heart rate; RPE, rating of perceived exertion; BLa, blood lactate concentration; CR, cycle rate; CL, cycle length. Within-group differences: *P<0.05; between-group differences: #P<0.05.

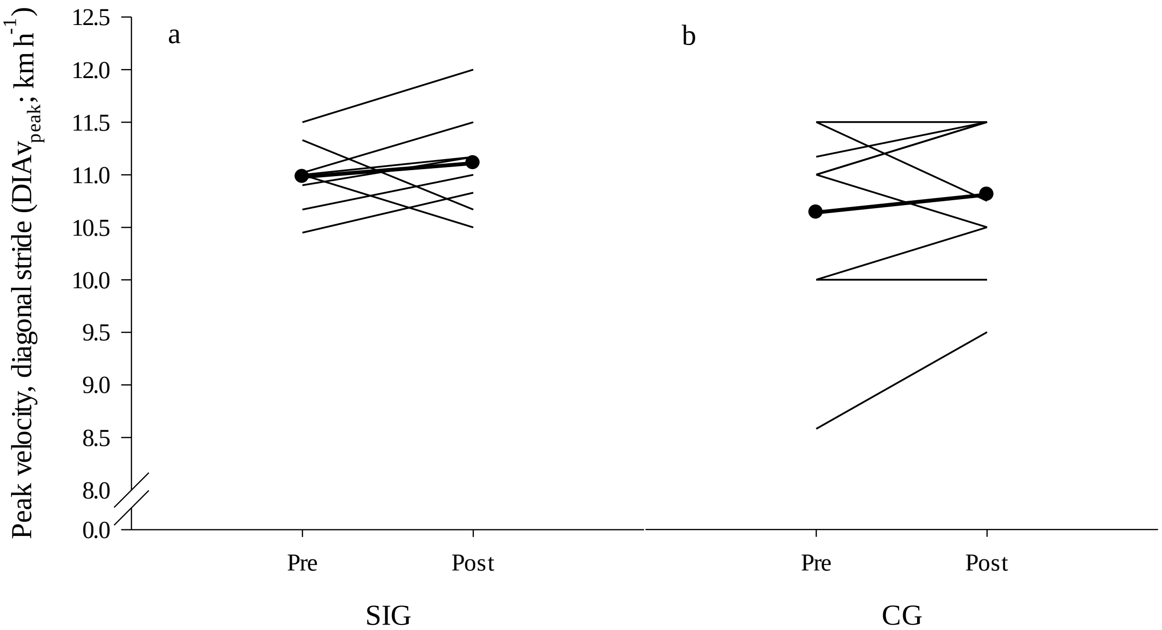

Figure 10a and b. Individual data points for peak velocity in diagonal stride before (Pre) and after the intervention period (Post) for the upper body sprint interval training group (SIG) and the control group (CG). Mean values are represented by the thick line with black circles.

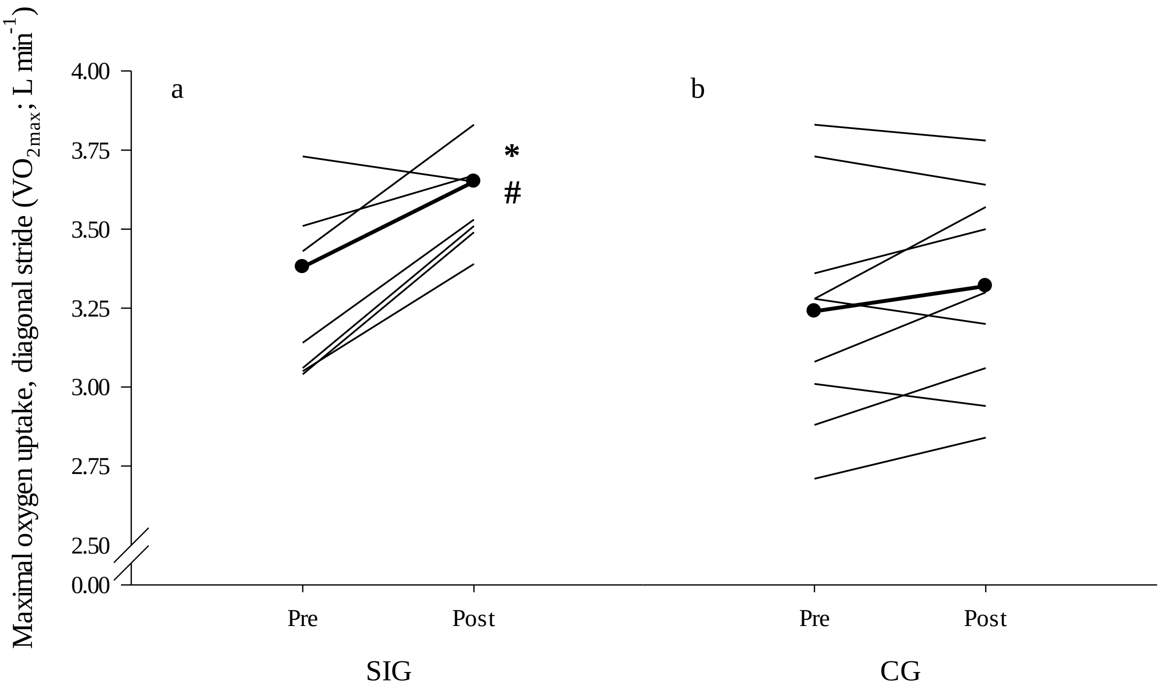

Figure 11a and b. Individual data points for maximal oxygen uptake in absolute terms in diagonal stride before (Pre) and after the intervention period (Post) for the upper body sprint interval training group (SIG) and the control group (CG). Mean values are represented by the thick line with black circles. Significant within-group changes: $^{*}P<0.05$; Significant different change from pre to post between groups: $^{\#}P<0.05$.

4.0 DISCUSSION

The present study was designed to compare the effects of upper body sprint interval training with continuous endurance training in improving endurance performance, peak aerobic capacity, work economy and kinematics in classical roller skiing, as well as upper body strength and power, among highly trained female junior cross-country skiers. The main findings were that both groups showed considerable improvements in peak aerobic capacity in double poling from both types of upper body training, but no significant differences between groups were found in endurance performance, work economy or kinematics in neither double poling nor diagonal stride. The sprint interval training group had larger improvements than the control group in DIA VO_{2max}, as well as in upper body maximal strength (1RM) and power.

4.1 Training intervention

Preceding this study, we emphasized an initial physical fitness evaluation and laboratory familiarization visit for introduction of testing and training procedures, to ensure minor learning effects between pre- and post-test. As no randomization procedures were used, an initial evaluation of each subject was considered essential. Although it is desirable from a theoretical point of view to randomize the group assignment without regard to school, it was not deemed practical from field experience. This study comprised a baseline period, during which the subjects` training was monitored and the strength training regime standardized. Therefore, all subjects were familiarized to the test exercises and the intervention training before the start of the study. This ensured that the same basic training pattern was followed during the subsequent intervention period. Each training group was followed up weekly by the investigators and educated coaches during the intervention training period. Here, emphasis was placed on close and similar supervision and monitoring of both groups regarding the implementation of intervention sessions and total training throughout the period.

The compliance of the scheduled training in the intervention period reached an acceptable level for inclusion for statistical analysis (≥75%) in both groups, with 83% and 77% in SIG and CG, respectively. As training data were based on the skiers` personal training diaries, inter-individual variation in the training quantification may have occurred. However, it has been concluded that self-reported training duration and intensity distribution in elite skiers is in accordance with their HR profiles [80, 82], and therefore the differences found in training data between groups are considered highly valid. During the intervention period, SIG was found to increase anaerobic (i.e. experimental manipulation) and speed training more than

CG, whereas CG trained more general strength (GST) and low to moderate intensity training (INT2) than SIG. More speed training performed in SIG may have contributed to supplement the effects of the anaerobic upper body SIT on neuromuscular/musculoskeletal characteristics (i.e. potential neural adjustment and changes in force-generating capacity). Although CG trained more GST and INT2 during the intervention period, both of these training modes are of submaximal workload, and therefore not considered to violate the internal validity (i.e. confounding factor) of the examined training effects of upper body CET. Moreover, CET employing DP on roller skis in varied terrain has previously been demonstrated by Terzis et al [49] to require greater power/intensity during uphill segments. Compared to CET, SIT requires a lower total exercise volume due to its vigorous nature and high power requirements (i.e. high anaerobic glycolytic energy contribution and neuromuscular load) [54]. Therefore, a small supplementation of SIT into the traditional endurance training regime poses a considerable additional strain on both aerobic and anaerobic biochemical/physiological systems, in addition to neuromuscular/musculoskeletal stimuli [53, 54].

4.2 Performance and peak aerobic capacity

4.2.1 Double poling

The present study showed no significant group differences in roller ski performance in DP after an 8-week training period, although CG had a significant improvement following increased upper body CET. The effect size (ES) indicates small positive effects of CG vs SIG. In SIG two of the subjects (representing 25% of the group) were found to have a substantial decline in DP performance, in contrast to improved values in related measured parameters (i.e. peak aerobic capacity and upper body maximal strength and power). Therefore, an additional statistical analysis was conducted where these two subjects were excluded. These findings revealed a significant ~6% increase in DP performance from pre-to post-test in SIG. These results are more consistent with the study from Nilsson et al [68], where SIT (20-s bouts) on a DP ergometer demonstrated to increase upper-body capabilities of well-trained cross-country skiers. Thus, one limitation of the present study is our small sample size. Our ability to determine statistical significance was reduced when significance, in fact, could have been reported, as supported by Cantrell et al [83]. Furthermore, recent studies have suggested that training designed to improve DP performance should focus on upper body exercises at high intensity and ski-specific movement patterns [47, 84, 85], which supports the effectiveness of upper body SIT in modern cross-country skiing.

However, in the current study we found improvements in DP performance after increased upper body CET at predominantly low-to-medium intensity. These data correspond to the results from Terzis et al [49], where long duration, low-to-moderate intensity workouts using only the DP resulted in improved performance in a 10 km classical time-trial due to induced morphological (i.e. muscle fiber type changes) and metabolic adaptations (i.e. increase enzyme activities and capillarization of type I and type IIA fibers) of the triceps brachii muscle. Although, in both cases, training was mostly of low-to-moderate intensity, it did contain shorter sections of high intensity. The arm-shoulder muscles of the skiers became activated intensively during the training as the skiers were only allowed to use DP. This means that the upper body was greatly engaged during the shorter uphill segments of the tracks. Hence, the same morphological adaptations (bi-directional adaptation of MHC isoforms toward MHC IIA) observed in the study by Terzis et al [49] has been found after intensive SIT and strength training in leg muscles [86] but it can also occur in arm muscles. This may indicate that it is possible to induce considerable adaptation in specific arm muscles also with mixed low/moderate intensity endurance training. Muscle biopsies measures were not obtained in this study, so it is unclear which morphological and metabolic adaptations contributed to the increased DP performance.

Although the current study did not measure performance directly, previous investigations have revealed that the peak velocity (v_{peak}) that can be attained during an incremental test to exhaustion by a cross-country skier is a good predictor of performance [48, 77]. The reason for this is probably that v_{peak} is influenced not only by VO_{2max} and work economy, but also incorporates anaerobic capacity and neuromuscular/power characteristics [50]. Moreover, skiing velocity is the product of the frequency of propulsive force production (CR) and the distance between force cycles (CL). In general, faster skiers have greater CL than their slower competitors [5, 16, 44]. In the present study the finding of unchanged kinematical responses (CL and CR) at v_{peak} in DP, both within and between groups following training, might be explained by different strategies used by the skiers within both groups; some control DP velocity with high CR and low impulse of force, whereas others may have used a strategy with longer CL and higher impulse of force [48]. An increased CL following SIT was expected, but cycle characteristics probably remained unchanged due to no change in performance.

Interestingly, both groups demonstrated great improvements in VO_{2peak} in DP from both types of upper body training. Although SIG increased VO_{2peak} by 4.5% more than the CG, no significant group differences were revealed. The ES indicates moderate positive effects of SIG vs CG. These findings are in contrast to Nilsson et al [68], who found an unchanged VO_{2peak} following 6-weeks SIT (20-s bouts), three times a week in DP on a poling ergometer. Our findings are of interest considering that ample evidence demonstrates that SIT results in similar or larger adaptations than CET [56, 59, 63, 64]. It was shown that six weeks of SIT with four to six 30-s bouts or six SIT-sessions performed over two weeks resulted in similar adaptations as CET ranging from 45 to 60 min [56] or 90 to 120 min in duration [64] of cycling, respectively. VO_{2peak} appears to respond similarly to both distinct intensities of endurance training [56]. Moreover, SIT has been shown to increase the maximal activity of aerobic enzymes [64]. The study by Burgomaster et al [56] in particular demonstrated significant improvements in VO_{2peak} at a substantially lower training volume. This indicates that SIT is a very time-efficient strategy to induce rapid adaptations in skeletal muscle and exercise performance, comparable to adaptations following CET [64].

In contrast to the majority of the trials, the SIT in the present study was added as a supplement to the skier's regular training regimes, and the groups did not differ in weekly training volume. The non-significant greater improvement in DP VO_{2peak} in SIG may indicate that specific SIT-sessions incorporated into a traditional endurance training regime are a powerful stimulus for further upper body performance adaptations in female skiers. Since upper body VO_{2peak} has shown high correlations (ranging from 0.60 to 0.89) with race performance [15, 21, 22], the great response observed in our study may indicate that the upper body musculature in female skiers is still underdeveloped. Although, no underlying mechanisms were investigated by e.g. muscles biopsies and DXA-scan in the current study, Holmberg et al [15] suggested that higher VO_{2peak} values during DP are achieved by increasing skeletal muscle mass in the upper body, increasing the capacity of peripheral vasodilation and oxygen extraction of upper body muscles, and ultimately by technical modifications that would result in the incorporation of a larger total amount of muscle mass.

Given that peak HR in DP increased significantly in CG while remaining unchanged in SIG may indicate that CET induces more peripheral adaptations in the upper body musculature (i.e., increase in capillarization/mitochondrial density) in preference to central adjustments, which is in accordance with previous findings [58, 67, 87]. Conversely, SIT appears to induce more central adaptations, as evidenced by stroke volume improvement [88]. Stroke volume can increase through a higher left-ventricular contractile force and/or through an increase in cardiac filling pressure, which raises end-diastolic volume and resultant stroke volume [58, 67]. A tendency towards increased peak VE in SIG may strengthen the assumptions of more central adaptations following SIT. According to the literature, greater peak values of BLa in DP could be expected following SIT, since findings have shown that peak BLa can be used as a rough estimate of anaerobic capacity [48]. SIT has been found to improve anaerobic performance due to induce alterations in glycolytic enzymes, muscle buffering, and ionic regulation [62, 64-66]. In the current study, both groups increased peak BLa in DP following training, and in contrast to the literature, only CG reached a significant level. This might be due to fact that the majority of studies comparing SIT with CET examine leg exercise, but the physiological responses during upper body work seem somewhat different from those obtained during leg exercise [70, 89]. Since the upper body is characterized by lower muscle mass, CG was probably prone to accumulate higher BLa than usually during leg or whole-body endurance training, due to the smaller part of active skeletal muscles in the upper body that can consume lactate during exercise [90].

4.2.2 Diagonal stride

Since both groups entered the intervention period with a high physical fitness level, it was not unexpected that findings revealed no significant change in DIA performance, either within or between groups following the 8-week period. As the classical roller skiing training emphasized DP to a greater extent in the intervention period, performance development in DIA was not necessarily expected. These data can likely be seen in conjunction with significantly unchanged peak kinematical responses (CL and CR) in DIA, both within and between groups following the training period. Our findings are of interest since Fabre et al [26] recently revealed that DP incremental test on a treadmill appears to be a more accurate test to predict skiing performance than DIA test, as explained by the importance of the upper body contribution in the cross-country skiing performance. Moreover, the combination of both tests permits to obtain an additional good performance indicator [26].

In the present study, SIG demonstrated 6% significant greater improvements than CG (8.6% vs 2.6%) in VO_{2max} during DIA. The ES indicates large positive effects of SIG vs CG. Several studies have shown a corresponding increase in VO_{2max} in the range of ~4-13.5% following SIT, typically measured during an incremental test to exhaustion [56, 59, 67, 91, 92]. In contrast, most studies on well-trained individuals primarily examining SIT with leg exercises reported unchanged VO_{2max} values [93]. The increase in VO_{2max} and oxidative enzymes that was reported in previous studies may indicate that the current SIT-protocol may have contributed to changes in the capacity to produce energy via oxidative metabolism. Findings indicate that SIT taxes both the anaerobic and aerobic energy pathways to a substantial extent, with the rate of glycolysis progressively decreasing and the aerobic energy production increasing as the exercise is repeated [94]. Peak VE was also found to increase significantly from pre-to post-test in SIG, which may also have influenced the enhancement in $VO_{2max.}$

These aforementioned factors may partly explain the observed increase in DIA VO_{2max} in SIG, but disparages not that other factors have influenced this improvement compared to CG. Therefore, it remains uncertain if and how other changes in the total training of the skiers (e.g. training content, type of sessions, quality of implementation of the endurance training etc.) may have influenced possible changes in VO_{2max}. These factors should be taken into consideration in future studies. However, it can be speculated that the non-significant greater improvement found in DP VO_{2peak} in SIG compared to CG may have contributed to the increase in the whole-body $VO_{2peak.}$ This is supported by Rusko [22] who stated that improved upper body VO_{2peak} influenced combined upper and lower body (and skiing) $VO_{2max.}$ Interestingly, in the present study the VO_{2peak} DP/ VO_{2peak} DIA ratio increased 1.8% and 3.2% from pre to post-training and reached 90.8% and 92.6% in SIG and CG, respectively. This ratio emphasizes the capability of the skier to consume oxygen when the main part of the work is produced only by upper body muscles (during DP) against by the whole body (during DIA), and has been found to be an accurate predictor of race performance in skiing [26].

4.3 Work economy and kinematics

The velocity achieved in endurance competitions depends on several physiological and mechanical factors where one of these factors is work economy [38]. Based on a previous study by Nilsson et al [68] we expected a better work economy following upper body SIT. However, in the current study work economy remained unchanged from pre-to post-testing, within and between groups for both DP and DIA. Moreover, the finding of a stable work economy is in accordance with previous observations in well-trained endurance athletes [95, 96]. Although seasonal changes in work economy have been stated [97, 98], this was not necessarily expected during this studies 8-week training period on highly-trained athletes. Since cross country skiing is a highly technically demanding exercise with involvement of both the arms and the legs, technical improvements in different skiing techniques have been shown to lead to increased work economy [98]. Therefore, the stable work economy found in our cases may be attributed to the non-significant changes revealed in the submaximal kinematical responses (CL and CR) in both DP and DIA, within and between groups, following the training period. Since specific strength and power training have been attributed to enhance the ability to produce force through more effective kick and pole pushes and thereby increase CL, it was more expected that SIG would improve technical skills and thereby increase work economy following the training period. However, it is reasonable that a modification of established technical patterns (i.e. cycle characteristics) in highly-trained skiers does not necessarily occur only by an 8-week training period.

4.4 Upper body strength and power

It was hypothesized that upper body SIT would be more effective than CET in improving maximal upper body strength (1RM) and average power (40% of 1RM) in a poling specific exercise. This is confirmed by our findings showing that SIG significantly increased maximal strength and tended to improve average power more than CG following training. The ES indicates large positive effects on maximal strength and medium positive effects on average power of SIG vs CG. According to the literature, SIT has been found to cause significant strain on the neuromuscular/musculoskeletal system (i.e. potential neural adjustment and changes in force-generating capacity) [54]. Furthermore, the 30-s (or ~20-25 repetitions) SIT-sessions performed in the current study (i.e. uphill DP and roller board in kneeling position at steep incline) emphasized upper body exercises with high resistance/power output and maximal mobilization, which further strengthens the effects of SIT on specific maximal upper body strength and power. Moreover, the maximal strength gains observed in SIG (17.6%) are in accordance with strength gains (15%) observed following a 9-week maximal upper body strength training regime among female skiers [32]. Although SIG demonstrates a significantly greater gain in these variables than CG, it is remarkable that CG revealed considerable increases as a result of greater emphasis on upper body CET. This might be explained by the high intensive activation of the upper body muscles as the skiers were only allowed to use the DP in varied terrain. This is supported by Terzis et al [49] who demonstrated corresponding morphological adaptations in the arm muscles after extensive upper body CET as seen following strength training and SIT in leg muscles.

A target of strength regimes for endurance athletes is to increase specific strength and power with a minimal amount of hypertrophy. Over the 8-week duration of this study there were no changes in body mass, however, body composition was not measured. This data might indicate that changes in upper body strength and power found were primarily the result of improved muscle recruitment rather than muscle hypertrophy. Nesser et al [20] suggested that any unnecessary weight gain in skiers could reduce relative aerobic capacity and increase the total weight carried throughout a race. However, Stöggl et al [40] suggested that focus on increasing muscle mass in the trunk appears important for the modern skiing performance (i.e. peak velocity). Due to considerably increased race velocities in modern cross-country skiing, maximal upper body strength and power have been demonstrated to be critical determinants of skiing performance [32, 34, 35, 68]. The high response observed in the current study may be related to the fact that arm muscles in female cross-country skiers are still underdeveloped, and thereby, upper body strength and power reasonably are limiting factors for their skiing performance. However, Stöggl et al [99] revealed that strength and power per se seem not to be major determinants of performance in skiers, whereas coordination of these capacities within the different and complex skiing movements seems to be the discriminating factor. Since no technical modifications (i.e. cycle characteristics) were revealed even though great strength and power developments, it is reasonable that these female skiers may benefit from special attention to proper technique (i.e. higher leg and arm forces, shorter ground contact with longer recovery and longer CL) and thereby potentially transfer these improvements into skiing performance (i.e. attaining higher skiing speeds).

4.5 Practical applications

From a practical point of view, the findings of this study give important key issues for training programs and evaluations for junior female cross-country skiers and their coaches. The high adaptive responses observed in the current study, may be related to the fact that upper body capabilities in junior female cross-country skiers still are underdeveloped, and thereby, limiting factors for the their skiing performance. Therefore, greater emphasis should be put on specific upper body training among this group of athletes. The findings of this study suggest that upper body aerobic capacity, as well as upper body strength and power can be improved both by adding upper body SIT and CET as key supplement to their traditional endurance training. The fact that SIT was substantial more effective in improving upper body strength and power than CET, suggest that SIT is a time efficient training modality. In addition, it appears that these female junior cross-country skiers may benefit from greater attention to proper technique, and thereby may potentially transfer these increased upper body capabilities into greater skiing speed and performance. However, this study was only performed over 8 weeks, and the effects of these distinct forms of upper body training over a longer time-scale among highly trained athletes still requires further investigation.

4.6 Methodological consideration

Although roller skiing is a regularly used training mode for cross-country skiers, it is also a separate sport. Therefore, the data from the current study may be utilized to roller skiing performance level. Despite some differences between skiing on snow and roller skiing, the basic principles of propulsion are equal. Thus, our results are probable applicable to performance on snow as well, as based on the evaluation of Sandbakk and colleagues [5].

Recently, it has been concluded that self-reported training duration and intensity distribution in elite endurance athletes is in accordance with their HR profiles [80, 82]. Although daily self-reported training is found valid, some inter-individual variation in the training quantification may have occurred. Though, such information may not provide a complete picture of training among cross-country skiers. For example strength, anaerobic and speed training is often recorded in terms of hour, rather than by loads, series and numbers of repetitions. However, additional common quantification guidelines would probably improve accuracy.

4.7 Conclusion

This present study demonstrates that both upper body sprint interval training and continuous endurance training are remarkably effective in improving peak aerobic capacity in double poling, but no significant group differences were found in endurance performance, work economy or kinematics in neither double poling nor diagonal stride roller skiing following these diverse forms of upper body training. The sprint interval training group demonstrates greater improvements than the control group in peak aerobic capacity in diagonal stride, as well as in specific upper body maximal strength (1RM) and average power. The high training response observed in the current study may be related to the fact that upper body capabilities in female junior cross-country skiers still are underdeveloped. Overall, these data indicate a large potential for female junior skiers to improve their physiological capacities by increased focus on upper body training in general, and that sprint interval training tends to be particularly effective for improving strength and power characteristics.

Acknowledgements

The study was financially supported by the Norwegian Olympic Committee, Mid Norway department. I would like to express my gratitude to Dr. Boye Welde and Dr. Øyvind Sandbakk, my supervisors, for their guidance, encouragement and useful critiques during this study. I would also like to thank all of the skiers and coaches involved for their cooperation and participation, Sindre Østerås for supervising the strength tests and finally my college and friend Andrea Hovstein Kruken for being an excellent team player during the whole process.

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