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Review article

A Systematic Review of the Effects of Strength and Power Training on Performance in Cross-Country Skiers

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Abstract
To identify and evaluate current scientific literature concerning the effect of strength, power and speed training on relevant physiological and biomechanical characteristics and performance of competitive cross-country skiers (XCS), the databases Scopus and PubMed were searched systematically for original articles in peer-reviewed journals. Of the 599 studies retrieved, 12 met the inclusion criteria (i.e., assessment of outcome measures with relevance for XCS performance; involvement of traditional resistance training; application of external resistance to the body; intervention longer than 4 weeks; randomized controlled trial). The methodological rigor of each study was assessed using the PEDro scale, which were mostly poor-to-fair, with good methodological quality in only two articles. All of the strength/power/speed interventions improved 1RM (0.8 - 6.8 ES), but findings with respect to jump performance, ability to generate force rapidly and body composition were mixed. Interventions demonstrated moderate-to-high ES on XCS specific performance compared with control (mean ES = 0.56), but the pattern observed was not consistent. None of the interventions changed anaerobic capacity, while in most studies VO_{2max} was either unchanged or increased. Work economy or efficiency was enhanced by most of the interventions. In conclusion, present research indicates that strength training improves general strength, with moderate effects on XCS performance, and inconclusive effects on work economy and VO_{2max}/VO_{2peak}. Strength training with high loads, explosive strength training, or sprint interval training seem to be promising tools for modern XCS training. Future investigations should include long-term (e.g., >6 months) strength training to allow sufficient time for increased strength and speed to influence actual XCS performance. Moreover, they should include both sexes, as well as upper- and lower-body muscles (trained separately and together) and employ free weights and core training. Methodological differences and limitations highlighted here may explain discrepancies in findings and should be taken into consideration in future research in this area.

Key words: 1 repetition maximum; distance performance; jump performance; randomized controlled trial; sprint; time trial; work economy.

Introduction

Cross-country skiing (XCS) has developed extensively since its debut almost 100 years ago at the first Winter Olympics in 1924 in Cortina. Improvements in equipment, more effective preparation of the tracks and skis, as well as more efficient training based on both experience and scientific research have led to substantially better performance and higher racing speeds. At the same time, XCS racing formats, including the shorter sprint and team sprint events, have undergone dramatic change and today more than 90% of the races involve mass-start, where rapid accelerations and high finishing speed are decisive for success (Sandbakk and Holmberg, 2014; Stöggl and Müller, 2009).

The biomechanics of XCS are highly complex (Smith, 1990), with propulsive forces being produced by the musculature of both the upper and lower body and transmitted to the ground via the skis and poles. Because of this complexity, along with the wide range of speeds (5 - 70 km·h^{-1}) and types of terrain (inclines of -20 to 20%) involved (Sandbakk and Holmberg, 2014), elite XCS requires a variety of capabilities, including considerable aerobic and anaerobic power, strength, speed and endurance, as well as highly developed technical and tactical skills.

During recent decades, the novel racing formats alluded to above have contributed to the development and/or modifications of both training (Sandbakk and Holmberg, 2017) and skiing techniques (Stöggl and Müller, 2009; Stöggl et al., 2008), resulting in higher production of force (Holmberg et al., 2005; Stöggl et al., 2011; Stöggl and Holmberg, 2016; Stöggl et al., 2008), greater acceleration (Wiltmann et al., 2016) and more power and speed (Pellegrini et al., 2018). For example, to attain high speed with the double-poling (DP) technique, both peak pole forces and poling force impulses must be great (Holmberg et al., 2005; Stöggl and Holmberg, 2011; Stöggl and Holmberg, 2016) and the timing of force generation well-coordinated (Stöggl and Holmberg, 2011; Stöggl and Holmberg, 2016). For elite skiers moving at maximal speed, no more than approximately 0.2 s is available for propulsion while employing the DP technique (Stöggl et al., 2011; Stöggl et al., 2013; Stöggl et al., 2010a; Stöggl and Müller, 2009), which is comparable to the period of contact between the foot and ground while running (Weyand et al., 2010), stressing the importance of rapid force production and attainment of peak force.

Obviously, strength is important in connection with most sports (Wernbom et al., 2007) and several strength training interventions have been shown to improve both short- and long-term endurance. This can be achieved by optimizing the rate of production of muscle force (Beattie et al., 2014) through appropriate neuromuscular adaptations (e.g., enhanced stiffness of muscles and tendons, improved recruitment and synchronization of motor units, rate coding, intra- and intermuscular coordination, and neural inhibition). In theory, a XC skier who improves

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his/her strength will move more economically at submaximal speeds (reduced relative force required), with enhanced endurance-specific muscle power that can generate the elevated power output and more rapid velocities demanded by modern XC skiing techniques (see above).

Several cross-sectional and correlative studies have reported positive associations between the level of strength and performance of XC elite skiers (among others, Mikkola et al., 2010; Niinimaa et al., 1978; Sandbakk et al., 2011; Stöggl et al., 2011; Wiltmann et al., 2016). More recently, retrospective investigations have provided additional details concerning the manner and schedule by which elite skiers train strength (Sandbakk, 2017; Sandbakk, 2018; Sandbakk and Holmberg, 2014; Sandbakk and Holmberg, 2017; Solli et al., 2017; Solli et al., 2019). In comparison, fewer researchers have utilized a randomized control trial (RCT) to evaluate the potential effects of strength and/or speed training instead of or in addition to routine training.

Therefore, the aim of the current systematic review was to provide comprehensive and critical commentary on the available scientific literature describing the effects of strength, resistance and/or speed training on the physiological determinants, technical aspects and performance of competitive XC skiers.

Methods

Approach

To identify articles that assess the effect of strength training on the performance of competitive cross-country skiers, we searched for relevant titles, abstracts and keywords in the databases PubMed and Scopus on December 20, 2021, employing the following profile: TITLE-ABS-KEY (("cross country skiing" OR “XC ski*” OR "cross-country skiing" OR "Nordic skiing" OR "classic style" OR "skating technique" OR "skate* technique" OR "Nordic combined" OR biathlon) AND (strength OR "strength training" OR “resistance training” OR "heavy load" OR "heavy strength" OR “weight training” OR power* OR force* OR "power output" OR "strength endurance" OR weightlifting OR "explosive strength" OR “concurrent training” OR "speed training" OR "maximal strength" OR "maximal force" OR isometric* OR isokinetic* OR "jump training" OR “plyometrics” OR "lean body mass" OR "lean mass" OR "muscle mass" OR "muscle hypertrophy" OR "hypertrophy" OR "intramuscular training" OR "fibre distribution" OR "body composition") AND NOT ("ice hockey" OR "ice skating" OR "ice speed skating" OR "speed skating" OR "short track")). These search terms were modified as needed to meet the requirements or fit the specific nature of these two databases.

Strength training was defined as activity involving a load equal to at least body weight and/or free-weight and/or machine-based exercise. The sub-categories considered were 1) maximal strength training designed to maximize force development through high-load, low-velocity exercise (i.e., 90 - 100% 1RM or supramaximal load aiming to promote intramuscular coordination); 2) muscle hypertrophy training in the form of maximal strength training meant to increase muscle cross-sectional area; 3) explosive strength (strength-speed and speed-strength) training designed to improve the rate of force development (RFD) and allow more rapid attainment of maximal power output through medium-to-high-load, high-velocity exercise (i.e., squat jumps, Olympic lifts); 4) reactive strength training that targets stiffness of the muscles and tendons and the stretch-shortening cycle (SSC) through the use of low-load, high-velocity exercise (i.e., jumps, drop jumps, hops, bounds, sprints); and 5) sport-specific sprint interval or speed endurance training (sprints ≤30 s in duration) intended to maximize acceleration and/or speed/power.

Inclusion criteria

The criteria for inclusion of a publication in this analysis were as follows: 1) assessment of outcome measures related to XCS performance; 2) an experimental design involving traditional resistance training and/or applications of external resistance to the body and/or sprint interval training, with a control group and randomization (randomized controlled trials); and 3) interventions longer than 4 weeks. The outcomes reported in all studies that fulfilled these criteria were summarized.

Study selection

Data were extracted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009). First, the search results were imported into EndNote X20 (Clarivate Software, Philadelphia, US) for removal of duplicates before being exported to Rayyan QCRI software (Rayyan Systems Inc. MA, USA). Thereafter, each study was first evaluated independently by both authors on the basis of the title of the journal in which it was published, then using the abstract and, finally, by complete review, following which articles fulfilling the inclusion criteria were analysed. Discrepancies were resolved by discussion. The PRISMA flowchart in Figure 1 illustrates schematically the protocol employed for data extraction.

The Physiotherapy Evidence Database (PEDro)

The 11-item scale of the Physiotherapy Evidence Database (PEDro), designed for assessing the methodological quality of randomized controlled trials (Maher et al., 2003), was applied by the principal investigator to the articles included for analysis. The factors rated included randomness of allocation; concealment of allocation; comparable characteristics of the experimental and control groups at baseline; blinding of participants, researchers, and assessors; analysis with intention to treat; and adequacy of follow-up. One point was allocated for each criterion fulfilled and studies scoring 9 - 10 were considered to be methodologically excellent (excellent internal validity), with those with scores of 6 - 8 being considered good, 4 - 5 fair, and <4 poor. The Pedro scores for the experimental design studies assessed are shown in Table 1.

Our database search recovered 599 journal articles of potential relevance. After removing 177 duplicates, the titles and abstracts of the remaining 422 articles were screened with respect to the inclusion criteria. Full-text review of the 78 articles thus found to be eligible resulted in removal of 70 more (8 review articles, 55 which lacked a control group that performed endurance exercise only or were cross-sectional correlative studies, 5 involving no training of strength, jumping or speed, and 2 with no sprint-interval training), as well as inclusion of 4 additional articles referred to in one or more of those 70 publications. Finally, 12 articles were subjected to the PEDro scale analysis, while 19 others identified as cross-sectional and correlative are only taken up in the Discussion (Figure 1).

The results are presented as the percentage differences between the pre- and post-intervention values for all variables related to strength, performance during a time-trial and/or actual competition, time to exhaustion, peak power output, maximal speed, VO_{2max}, power/velocity at VO_{2max}, blood lactate response and anaerobic capacity, work economy or gross efficiency, body composition and biomechanical parameters for each of the groups individually, along with the associated p-values.

Effect sizes for the group x time interactions were calculated as the post- minus pre-intervention value for the intervention group minus the corresponding difference for the control group divided by a pooled standard deviation for the corresponding baseline values for the intervention and control groups, as follows:

$$ES = \frac{(IG_{post} - IG_{pre}) - (CG_{post} - CG_{pre})}{SD_{pre}}$$

where IG is the intervention group, CG the control group, pre and post the mean values pre- and post-intervention, respectively, and SD_{pre} the pooled standard deviation for the control and intervention groups at baseline calculated as

$$SD_{pre} = \sqrt{\frac{(n_1-1)SD_1^2+(n_2-1)SD_2^2}{n_1+n_2-2}}.$$

In addition, we applied a random-effects model to the standardized mean differences (Hedges' g). Dispersion was evaluated utilizing Q statistics, I^2 statistics, and the prediction interval. ES values <0.2 were considered trivial, 0.2 - 0.5 small, 0.5 - 0.8 medium and >0.8 large (Cohen, 1988). In some cases, data required for the calculation of percentage differences or effect sizes (ES) were missing. The forest plot was generated with the R-Studio program (2021.09.0 Build 351).

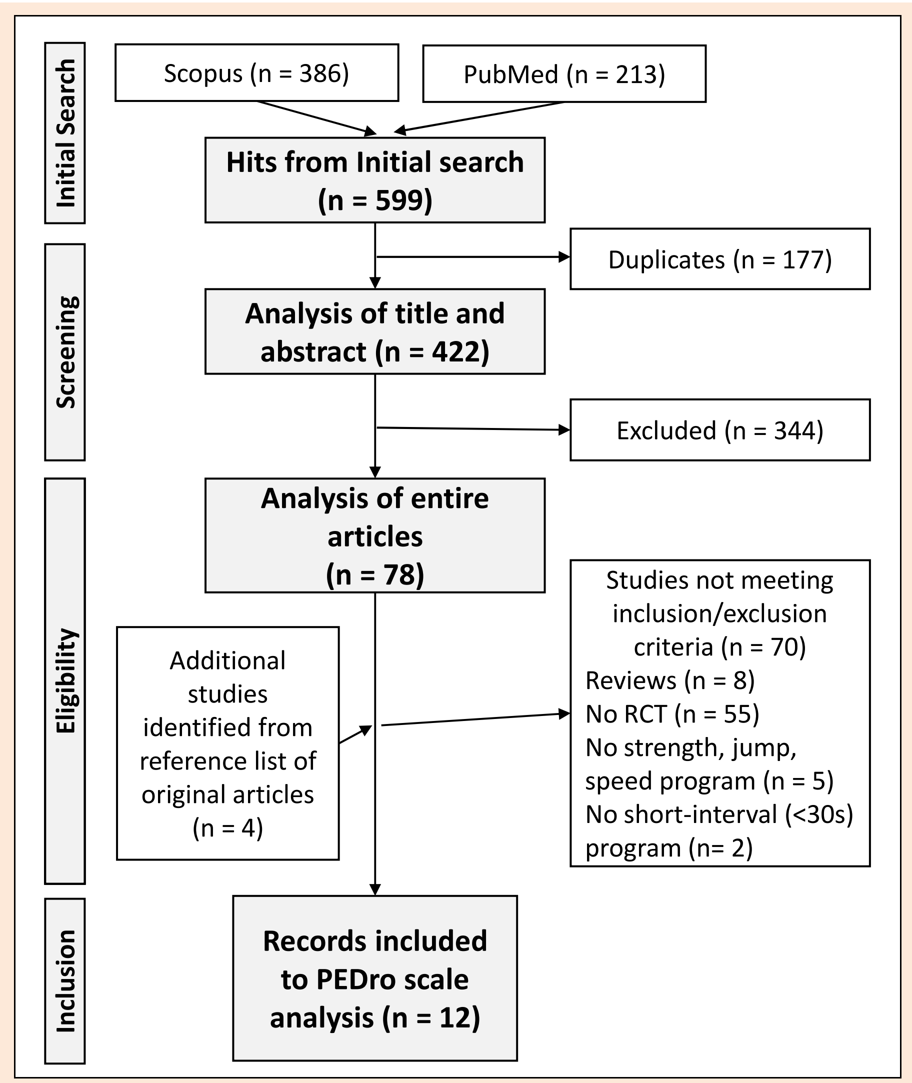

Figure 1. Selection of the articles subjected to evaluation with the PEDro scale and subsequently analysed in detail. RCT, randomized controlled trial.

Table 1. **Characteristics of the participants involved and study design employed in the articles analyzed, together with PEDro scores.**

Study	Subjects						Study design		
	N (I/C)	Sex	Age (years)	Height (cm)	Weight (kg)	VO_{2max} and/or (VO_{2peak} DP) ($L·min^{-1}$ and/or $mL·min^{-1}·kg^{-1}$)	Level of performance	PEDro-SCORE	Randomized?
Paavolainen et al. 1991	15 (7/8)	M	I: 19.8 ± 1.8 C: 20.0 ± 2.0	I: 179.5 ± 7.3 C: 178.5 ± 6.0	I: 71.4 ± 6.1 C: 69.2 ± 6.2	I: 4.9 ± 0.4/70.0 ± 5.3 C: 5.2 ± 0.4/ 75.0 ± 4.3	National-level XC skiers	5	No
Hoff et al. 1999	15 (8/7)	W	I: 17.9 ± 0.3 C: 18.0 ± 0.4	I: 166.7 ± 1.3 C: 168.7 ± 1.4	I: 166.7 ± 1.3 C: 168.7 ± 1.4	I: 3.1 ± 0.1/55.3 ± 2.2 C: 3.5 ± 0.4/ 55.3 ± 1.6	Regional XC skiers	7	Yes
Hoff et al. 2002	19 (9/10)	M	I: 20.4 ± 4.3 C: 19.2 ± 3.9	I: 175.7 ± 3.1 C: 183.0 ± 4.1	I: 70.7 ± 4.5 C: 75.6± 6.4	I: 4.9 ± 0.3/ 69.7 ± 2.3 (4.1 ± 0.4/ 58.7 ± 3.9); C: 5.2 ± 0.4/ 69.1 ± 2.3 (4.7 ± 0.4/ 61.1 ± 3.1)	Well-trained XC skiers	6	Yes
Østerås et al. 2002	19 (10/9)	M	I: 21.0 ± 1.6 C: 24.4 ± 5.0	I: 182 ± 2.8 C: 180 ± 3.8	I: 77.8 ± 4.9 C: 74 ± 3.5	I: (4.89 ± 0.6/ 63.1 ± 5.8); C: (4.39 ± 0.35/ 59.2 ± 2.8)	Highly trained XC skiers	5	Yes
Nilsson et al. 2004	20 (IT20-s = 6, IT180-s = 7 C=7)	M=12 W=8	IT20-s: 21 (19-24) IT180-s: 26 (20-33) C: 25 (20-29)	IT20-s: 178 (173-184) IT180-s: 176 (173-179) C: 180 (169-190)	IT20-s: 70 (62-72) IT180-s: 69 (62-74) C: 74 (61-92)	IT20-s: 63.8 ± 9.9 (54.2 ± 10.5) IT180-s: 61.6 ± 7.1 (53 ± 7.3) C: 63.4 ± 6.2 (53.7 ± 6.0)	Well-trained XC skiers	5	Yes (stratified for sex and level of performance)
Nesser et al. 2004	58 (20 drop-outs) (Cir=16, RB=21, SS=13, W=8, C=16)	M=29 W=29	Cir: 15.9 ± 1.1 RB: 16.2 ± 1.1 SS: 16.0 ± 1.3 W: 16.1 ± 1.2 C: 15.8 ± 1.7	Cir: 177.2 ± 6.6 RB: 174.6 ± 5.2 SS: 173.8 ± 4.6 W: 174.4 ± 5.7 C: 174.3 ± 6.8	Cir: 62.3 ± 6.1 RB: 59.7 ± 5.0 SS: 60.8 ± 4.7 W: 62.8 ± 5.6 C: 56.4 ± 5.9	NS	Adolescent XC skiers	3	No (geographical assignment)
Mikkola et al. 2007	19 (8/11)	M	I: 23.1 ± 3.9 C: 23.1 ± 4.5	I: 179.3 ± 6.1 C: 178.7 ± 4.8	I: 179.3 ± 6.1 C: 178.7 ± 4.8	I: 65 ± 6 C: 66 ± 3	National-level XC skiers	5	No
Losnegard et al. 2011	19 (9/10)	M=11 W=8	I: 21.2 ± 3.2 C: 21.7 ± 2.5	I: 176.7 ± 8.9 C: 173.3 ± 7.0	I: 71.4 ± 10.2 C: 67.8 ± 10.6	I: 64.7 ± 4.9 (G3/2: 61.6 ± 5.5) C: 64.6 ± 7.1 (G3/2: 62.0 ± 9.2	Competitive XC skiers	4	No (self-selected group)
Rønnestad et al. 2012	17 (8/9)	M	I: 19 ± 2 C: 20 ± 3	I: 180 ± 4 C: 180 ± 4	I: 69 ± 4 C: 69 ± 4	I: 66.4 ± 1.8 C: 66.0 ± 1.6	Well-trained Nordic Combined skiers	5	No (self-selected group)
Skattebo et al. 2016	16 (9/7)	W	I: 18 ± 1 C: 17 ± 1	I: 171 ± 5 C: 166 ± 6	I: 61 ± 4 C: 60 ± 9	Total group: 60 ± 5	Well-trained junior XC skiers	3	No (self-selected groups)

I, Intervention group; C, control group; M; men; W, women; Cir, circuit training; DP, double poling; ERG; ergometer; ET, endurance running interval training; G2, gear 2 skating technique; G3, gear 3 skating technique; IT20-s: 20-s sprint interval training group; IT180-s 180-s sprint interval training group; MET, muscular endurance training; NS, not stated; RB, roller board training; SS, ski-specific; STR, strength; STR_TRAD, Strength training traditional; STR_VIB, Strength training vibration; WT, weight training; XC, cross-country.

Table 1. Continue.

Study	Subjects						Study design		
	N (I/C)	Sex	Age (years)	Height (cm)	Weight (kg)	VO_{2max} and/or (VO_{2peak} DP) ($L \cdot min^{-1}$ and/or $mL \cdot min^{-1} \cdot kg^{-1}$)	Level of performance	PEDro-SCORE	Randomized?
Vandbakk et al. 2017	17 (8/9)	W	I + C: 18 ± 1	I + C: 166 ± 5	I + C: 60 ± 7	I: 56.1 ± 2.9 C: 53.8 ± 4.7	Highly-trained XC skiers	3	No (participants attending two different schools). Group allocation based on school attended
Øfsteng et al. 2018	29 STR VIB = 11, STR TRAD = 10, C = 8	M	STR VIB: 24 ± 6 STR TRAD: 23 ± 2 C: 27 ± 7	STR VIB: 182 ± 8 STR TRAD: 184 ± 8 C: 183 ± 7	STR VIB: 78.1 ± 8 STR TRAD: 76.8 ± 5.8 C: 77.0 ± 7.8	STR VIB: 67.3 ± 4.4 STR TRAD: 69.5 ± 6.0 C: 66.3 ± 7.9	Well-trained XC skiers	4	No (self-selected)

I, Intervention group; C, control group; M; men; W, women; Cir, circuit training; DP, double poling; ERG; ergometer; ET, endurance running interval training; G2, gear 2 skating technique; G3, gear 3 skating technique; IT20-s: 20-s sprint interval training group; IT180-s 180-s sprint interval training group; MET, muscular endurance training; NS, not stated; RB, roller board training; SS, ski-specific; STR, strength; STR_TRAD, Strength training traditional; STR_VIB, Strength training vibration; WT, weight training; XC, cross-country.

Results

Data extraction

The participants and characteristics of the training interventions involved in the 12 articles finally analyzed here, all published between 1991 and 2018, are shown in Table 1. Altogether, these studies included 12 control and 17 intervention groups of XC skiers: juniors in two investigations (Nesser et al., 2004; Skattebo et al., 2016), at the regional level in one, well-trained in five, and highly-trained or national/international in 6 (including Nordic Combined skiers in one case). A total of 263 skiers (on average, 9.9 ± 3.7 (range 6 - 21), of whom 65% were men) completed the programs. Their group mean VO_{2max} values (reported in all but one case (Nesser et al., 2004)) ranged from 53.7 - 75.0 $mL \cdot kg^{-1} \cdot min^{-1}$. The racing events ranged from sprint to distance.

Methodological quality and risk for bias

As documented in Table 1, the mean PEDro score for these studies, employed here as an indicator of methodological quality, was 4.6 ± 1.2 (range 3 - 7). This score indicated that two of the studies were of high-quality, seven of medium-quality, and the remaining three of low methodological quality. None concealed the group allocations (Item 3) or blinded the subjects (Item 5) or therapists (Item 6) and only one blinded the assessor (Item 7). It should be noted, however, that blinding of participants in this type of intervention is difficult. 67% of the studies listed eligibility criteria (item 1); analysis of intention-to-treat (Item 9) was fulfilled by all; and eight did not randomize the assignment of participants to the two groups.

Interventions for improving strength and/or power (Table 2)

The interventions designed to improve strength and/or power involved activities described as 1) maximal (Hoff et al., 2002; Hoff et al., 1999; Østerås et al., 2002) or heavy strength training (Losnegard et al., 2011; Ofsteng et al., 2018; Ronnestad et al., 2012; Skattebo et al., 2016), 2) explosive strength training (Mikkola et al., 2007), 3) sprint interval (Nilsson et al., 2004; Vandbakk et al., 2017), 4), explosive strength, heavy resistance strength and sprint training combined (Paavolainen et al., 1991) and 5) circuit, roller-board, ski-specific or weight training (Nesser et al., 2004).

Five of the interventions employed only exercise on machines (Hoff et al., 2002; Hoff et al., 1999; Ofsteng et al., 2018; Østerås et al., 2016; Skattebo et al., 2016). One study utilized a DP ergometer (Nilsson et al., 2004), two a combination of free weights and bodyweight resistance (Mikkola et al., 2007; Paavolainen et al., 1991), two a machine and free weights combined (Losnegard et al., 2011; Ronnestad et al., 2012), and one either circuit, roller-board, ski-specific training or weights (Nesser et al., 2004). Most of the interventions involved a single exercise (seated poling) (Hoff et al., 2002; Hoff et al., 1999; Østerås et al., 2002), two exercises (seated and standing poling together with triceps extension) (Ofsteng et al., 2018; Skattebo et al., 2016) or squats (Losnegard et al., 2011; Ronnestad et al., 2012)), whereas two involved more than 10 different exercises (Carlsson et al., 2017; Mikkola et al., 2007). Of the exercises, seated pulldown was used in seven (58%) cases (Hoff et al., 2002; Hoff et al., 1999; Losnegard et al., 2011; Ofsteng et al., 2018; Østerås et al., 2002; Ronnestad et al., 2012; Skattebo et al., 2016) and standing pulldown in four (33%) (Losnegard et al., 2011; Ofsteng et al., 2018; Ronnestad et al., 2012; Skattebo et al., 2016).

The average intervention period was 8.8 ± 1.9 (range 6-12) weeks, and the average number of strength sessions per week 2.7 ± 0.4 (range 2-3). More specifically, training of strength and/or power was scheduled twice (Losnegard et al., 2011; Ronnestad et al., 2012;

Vandbakk et al., 2017), two or three times (Skattebo et al., 2016) or three times (Hoff et al., 2002; Hoff et al., 1999; Mikkola et al., 2007; Nesser et al., 2004; Nilsson et al., 2004; Ofsteng et al., 2018; Østerås et al., 2002) each week. In one of the interventions, the extent of strength training was reported only as the percentage of the total number of training hours each week (Paavolainen et al., 1991).

The resistance/strength training typically involved three sets of each exercise, with 4 - 6 repetitions per set (10 repetitions for the standing DP exercise) at relatively heavy loads, specified as approximately 85% of maximal load or until repetition failure (Hoff et al., 2002; Hoff et al., 1999; Østerås et al., 2002). The sprint interval training consisted of 20-s sprints (Nilsson et al., 2004) with 2-min intervals of rest; 10-15-s (Mikkola et al., 2007) or 30-s sprints with 2-3 min rest (Vandbakk et al., 2017) or short maximal roller skiing sprints uphill (no exact duration provided) with 3-min intervals of rest (Nesser et al., 2004).

Table 2. Characteristics of the strength interventions involved in the articles analyzed.

Study	Type	Program overview	Time of year	Duration (weeks)	Frequency	Volume (duration) & intensity per session	ST/SIT replaced or added	ST supervised?	Endurance training	Total training
Paavolainen et al. 1991	The strength training for I was divided into explosive (E), heavy resistance (H) and sprint (S) training	E: Jumping and specific RS exercises (low loads/high velocities). H: Squats with barbells and exercises specific for skiers S: NS	Preparation period (autumn)	6	6-9 training sessions/ week – 34% (weeks 1-3) and 42% (weeks 4-6) strength.	15-90 min H: 70-90%1RM	NS	NS	1-4 h/session (66% first 3 weeks, 58% last 3 weeks) Documented (volume, frequency, exercise mode)	6-9 times/week (divided into END-STR)
Hoff et al. 1999	Maximal strength	Pull-down sitting on a bench	Preparation period (October-December)	9	3 sessions/week	I: 3x6RM (85% 1RM, with a 1-kg increase if 3 sets were completed successfully) C: General STR <60% 1RM or >20 reps	NS	Yes (every second week by the investigators, every week by trainers)	Mainly running during the first 4 weeks, then RS for the last 5 weeks Documented (volume, intensity)	Average weekly training volume of 8.5±0.8 and 9.2±1.2 h for I and C, respectively
Hoff et al. 2002	Maximal strength	Pull-down sitting on a bench	Pre-season (months, NS)	8	3 sessions /week	45 min/week I: 3x6RM (85% 1RM, with a 3-kg increase if 3 sets were completed successfully. 3-4 min rest between series) C: Strength endurance <85% 1RM	NS	Training sessions were monitored only three times by the investigator, but every week by the trainers.	9.15 h/week Documented (volume, intensity, exercise mode)	10 h/week

I, intervention group; C, control group; Cir, circuit training; DP, double poling; DPE, double-poling ergometer; END, endurance; ET, endurance running interval training; HIT, high-intensity; IT20-s: 20-s sprint interval training group; IT180-s: 180-s sprint interval training group; LIT, low-intensity; MET, muscular endurance training; MIT, medium-intensity; NS, not stated; RB, roller board; RM, repetition max; RS, roller skiing; STR, strength; STR, strength with vibration; WT, weight training.

Table 2. Continue…

Study	Type	Program overview	Time of year	Duration (weeks)	Frequency	Volume (duration) & intensity per session	ST/SIT replaced or added	ST supervised?	Endurance training	Total training
Østerås et al. 2002	Maximal strength	Pull-down sitting on a bench	Autumn prior to the start of competition season	9	3 sessions / week	45 min/week I: 3x6RM (85% 1RM, with a 3-kg increase if 3 sets were completed successfully. 2-3 min rest between series) C: Strength endurance <85% 1RM	Replaced	Training sessions monitored only three times by the trainers.	I: 12.8 h/week/ C: 10.5 h/week Documented (volume, intensity, exercise mode)	I: 14 h/week; C: 12 h/week
Nilsson et al. 2004	Sprint-interval training	DP interval training on an ergometer with 20-s (IT20-s) or 180-s (IT180-s) intervals	Preparatory period (May to first half of June) when the subjects had recovered from the competitive season	6 (16 sessions)	3 sessions / week	IT20-s: 20-s intervals with maximal power output and 120-s rest. Number of intervals increased from 11.7 to 14.7 over the training period. IT180-s: 180-s intervals with power output = 85% mean power output during 6-min performance test with 90-s rest (power increased 14% during this test to compensate for improvement in performance). Number of intervals increased from 6.0 to 7.5 over the training period.	STR replaced by 20- or 180-s sprint intervals	All training sessions were supervised and documented by the experimenters	Pre-dominantly low-intensity aerobic training performed as RS, running with and without poles and cycling. Documented (volume, intensity, exercise mode)	IT20-s: 8.4 h/week IT180-s: 8.1 h/week C: 8.6 h/week
Nesser et al. 2004	Circuit training (Cir) Roller board (RB) Ski-specific (SS) Weights (WT)	Cir: Pull-ups, push-ups, chair dips and sit-ups – using body weight only. RB: Roller board with adjustable angle for modifying resistance SS: Short maximal uphill RS sprints, ski-specific (arm and abdominal) plyometrics and uphill bounding with poles. Rest intervals: 3 min. WT: Lat-pullover with press, upright row, lat pulldown, triceps pulldown, bench press and seated row.	Summer training program	10	All groups 3 sessions / week	Cir//RB/ SS: ~30 min/session; Cir: To fatigue or for 30 sec (30-s rest between exercises) RB: 3–8RM (slow movements and long rest) for strength or 10–12RM (explosive and long rest) for power. Rest intervals: 3-5 min. SS: Short maximal (rest: 3 min). WT: ~25 min/session. Load varied from 3–8RM (slow movements) to develop strength to 10–12RM (slightly higher speeds) to develop power (rest: 3-5 min).	NS	Coaches monitored and led the training of one group each.	Cir: 4.7 h/week RB: 3.3 h/week SS: 6.6 h/week WT: 4.6 h/week Documented (volume, intensity, exercise mode)	Cir: 6.3 h/week RB: 4.8 h/week SS: 8.2 h/week WT: 5.7 h/week

I, intervention group; C, control group; Cir, circuit training; DP, double poling; DPE, double-poling ergometer; END, endurance; ET, endurance running interval training; HIT, high-intensity; IT20-s: 20-s sprint interval training group; IT180-s: 180-s sprint interval training group; LIT, low-intensity; MET, muscular endurance training; MIT, medium-intensity; NS, not stated; RB, roller board; RM, repetition max; RS, roller skiing; STR, strength; STR, strength with vibration; WT, weight training. Lat = lateral

Table 2. Continue…

Study	Type	Program overview	Time of year	Duration (weeks)	Frequency	Volume (duration) & intensity per session	ST/SIT replaced or added	ST supervised?	Endurance training	Total training
Mikkola et al. 2007	Explosive-type strength (general and sport-specific exercises)	Sport-Specific Rapid Force production (SSRF): DP RS or sprinting/bounding uphill with poles. Explosive strength (EXPLO): half squat, bench press, pullover, incline row, abdominal curl, back extension, leg press, lat pulldown, etc. Explosive training (EXPLO_A): running sprints (RS), alternative jumps (AJ), skating jumps (SJ), calf jumps (CJ).	Autumn, during the early phase of preparation for competition	8	3 sessions /week	The explosive training sessions lasted 30-75 min with volume for upper- and lower body being approximately the same. The typical speed training session consisted of 10-15-s sprints (running or DP) with 2-3-min recovery. The strength training usually consisted of 6-10 exercises (half squat, bench press, pullover, abdominal curls, back extensions, etc.) with 2-3x6-12 sets/reps. The training was performed with low loads, but at high velocities. SSRF: 10–15x10–15 s; EXPLO: 3 x 6–10 reps; RS: 3–6x30 m, AJ 4–6x20, SJ 4–6x20, CJ 4–6x10–15	Replaced	NS	Endurance training typical for XC skiers, such as RS, running and Nordic walking. Most of endurance training below anaerobic threshold. Documented (volume, intensity, frequency)	Total training volume was the same in both groups (I: 10.3±1.1 h and 10±0.5 h/week, C: 11.1±3.1 h and 11±1.0 h/week)
Losnegard et al. 2011	Maximal strength	Half squat, seated pulldown, standing DP and triceps press	During the basic preparatory period (beginning of June to end of August)	12	2 sessions /week	Training sessions approximately 45 min. Half squat, seated pulldown and triceps press: 3-4 x 5-10 reps; Standing DP: 3x10RM (Rest: 2-3 min)	Added	Individual supervision of the three first sessions by an investigator to ensure proper technique and appropriate work load.	I: 15.2±1.1 h; C: 15.3±0.7 h Documented (volume)	NS
Rønnestad et al. 2012	Heavy Strength training	Deep squat, seated pulldown, standing DP	Beginning of the preparation period	12	2 sessions /week	3-5 sets/session 3-5RM (70-80% 1RM) Standing DP: 10RM	Added	All athletes supervised by an investigator during all workouts for the first 2 weeks and thereafter once every week throughout the intervention.	No differences between the groups regarding the total volume of endurance training or distribution of this training within HR intensity zones. Documented (volume, intensity, frequency, exercise mode)	Same total weekly duration (including heavy strength training) by the two groups: 12.0±0.6 h

I, intervention group; C, control group; Cir, circuit training; DP, double poling; DPE, double-poling ergometer; END, endurance; ET, endurance running interval training; HIT, high-intensity; IT20-s: 20-s sprint interval training group; IT180-s: 180-s sprint interval training group; LIT, low-intensity; MET, muscular endurance training; MIT, medium-intensity; NS, not stated; RB, roller board; RM, repetition max; RS, roller skiing; STR, strength; STR, strength with vibration; WT, weight training. Rep=repetition

Table 2. Continue…

Study	Type	Program overview	Time of year	Duration (weeks)	Frequency	Volume (duration) & intensity per session	ST/SIT replaced or added	ST supervised?	Endurance training	Total training
Skattebo et al. 2016	Heavy strength training	Seated pull-down, standing DP and triceps press	Mid-September to end of November (late pre-competition period).	10	2-3 sessions /week	Three sets per exercise. Each session, including warm-up, lasted ~ 40 min. 10RM-4RM Each repetition was conducted with maximal mobilization in the concentric phase (lasting approximately 1 s), followed by a slower eccentric phase (2–3 s). Rest between sets: 2–3 min.	Added	To help ensure that the subjects lifted with proper technique and optimal load, they were encouraged to attend strength training sessions supervised by experienced coaches.	Both groups continued their normal aerobic and endurance training. I: 11.2±1.8 h: HIT 0.5±0.2 h; MIT 0.3±0.2 h; LIT 10.3±1.6 h C: 10.6±1.3 h: HIT 0.5±0.2 h; MIT 0.3±0.1 h; LIT 9.7±1.3 h Both groups performed similar amounts of ski skating (~ 27%), classic XC skiing (~ 28%), running (~ 40%), and other types of exercise (cycling, rowing etc.; ~5%). Documented (volume, intensity, frequency, exercise mode)	I: 13.8±2.3 h C: 12.7±1.4 h
Vandbakk et al.2017	Sprint-interval training	Session 1: 30-s upper-body sprint-intervals (DP RS) uphill outdoor at maximal sustainable effort Session 2: RB while kneeling.	June-November	8	2 sessions /week	6-8x30-s intervals of upper-body sprint separated by 2-3 min active rest (i.e., 15-20 min of total work duration for each session. Maximal sustainable effort (iso-effort).	Added	NS	I: LIT 9:48±1:57 MIT: 0:25± 0:08 HIT: 0:38±0:07 SI: 0:30±0:11; C: LIT: 10:10±2:54 MIT: 0:37±0:14 HIT: 0:36±0:10 SI: 0:00±0:01 Documented (volume, intensity, frequency, exercise mode)	I: 13:27±2:26 h; C: 13:54±3:44 h The total amount of training was individualized, i.e., not all skiers trained for exactly the same number of hours. Differences in the amount of LIT accounted for most of these individual differences.

I, intervention group; C, control group; Cir, circuit training; DP, double poling; DPE, double-poling ergometer; END, endurance; ET, endurance running interval training; HIT, high-intensity; IT20-s: 20-s sprint interval training group; IT180-s: 180-s sprint interval training group; LIT, low-intensity; MET, muscular endurance training; MIT, medium-intensity; NS, not stated; RB, roller board; RM, repetition max; RS, roller skiing; STR, strength; STR, strength with vibration; WT, weight training.

Table 2. Continue…

Study	Type	Program overview	Time of year	Duration (weeks)	Frequency	Volume (duration) & intensity per session	ST/SIT replaced or added	ST supervised?	Endurance training	Total training
Øfsteng et al. 2018	Heavy strength training (STR) with or without vibration (STR_VIB), in addition to their ongoing endurance training. In addition to endurance training (without any additional strength training) C was allowed to perform whole-body stability and core training.	Standing DP, seated pull-down and triceps press with or without 50-Hz vibrations of the wire in the custom-made pulldown apparatus. The daily undulating periodization of STR progressed toward fewer repetitions with higher loads. The first and last sessions each week were continued to failure, with the load adjusted in accordance with the RM principle. The second strength session each week was executed with a ~10% reduced load in comparison to the predicted RM (i.e., the sets were not continued to failure). The skiers were instructed to perform 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). On days when both END and STR were performed, the skiers were encouraged to perform STR first.	The intervention period started 5 weeks after the competitive season ended.	8	3 sessions /week	3 sets of each exercise First 3 weeks: 10, 12, and 6 repetitions during the 1st, 2nd and 3rd STR session of each week, respectively. Following 3 weeks: 8, 10, and 5 repetitions during the 1st, 2nd and 3rd session, respectively, adjusted to 6, 8 and 4 repetitions for the final 2 weeks. Inter-set rest periods of 2-3 min.	Added	All workouts were supervised by one of the investigators.	No significant difference in the weekly duration of END or its distribution as LIT, MIT, and HIT between the STR (13±3, 1±1,1±1 h) and C groups (10±5, 1±1, 1±0 h). No difference in the time spent running, cycling, performing DP, or other types of ski training each week (4±1, 1±1, 2±2 h, 7±2 h vs. 4±1, 1±1, 2±2.5±2 h, respectively). Documented (volume, intensity, exercise mode)	The STR groups trained more than the C group. During the intervention, the STR groups added traditional heavy strength training with or without vibration to their ongoing endurance training. The C group continued their usual endurance training, with no additional strength training.

I, intervention group; C, control group; Cir, circuit training; DP, double poling; DPE, double-poling ergometer; END, endurance; ET, endurance running interval training; HIT, high-intensity; IT20-s: 20-s sprint interval training group; IT180-s: 180-s sprint interval training group; LIT, low-intensity; MET, muscular endurance training; MIT, medium-intensity; NS, not stated; RB, roller board; RM, repetition max; RS, roller skiing; STR, strength; STR, strength with vibration; WT, weight training.

Strength training was reported to be fully or partially supervised in all of the investigations except three, where this aspect of the protocol was unclear (Mikkola et al., 2007; Paavolainen et al., 1991; Vandbakk et al., 2017). The total volume of endurance training varied considerably (4.8 - 15.3 h per week^{-1} divided into 3 - 9 sessions (Losnegard et al., 2011; Nesser et al., 2004)) and the level of detail provided regarding weekly volume and intensity varied.

Importantly, all of the studies involving additional strength training stated that the endurance training performed by all/both intervention groups was the same.

Findings

Strength and power

In all cases where 1RM was tested (Hoff et al., 2002; Hoff et al., 1999; Losnegard et al., 2011; Mikkola et al., 2007; Ofsteng et al., 2018; Østerås et al., 2002; Paavolainen et al., 1991; Ronnestad et al., 2012; Vandbakk et al., 2017), the intervention led to statistically significant greater improvement compared to the control group (+6-24%, ES: 0.80-6.81).

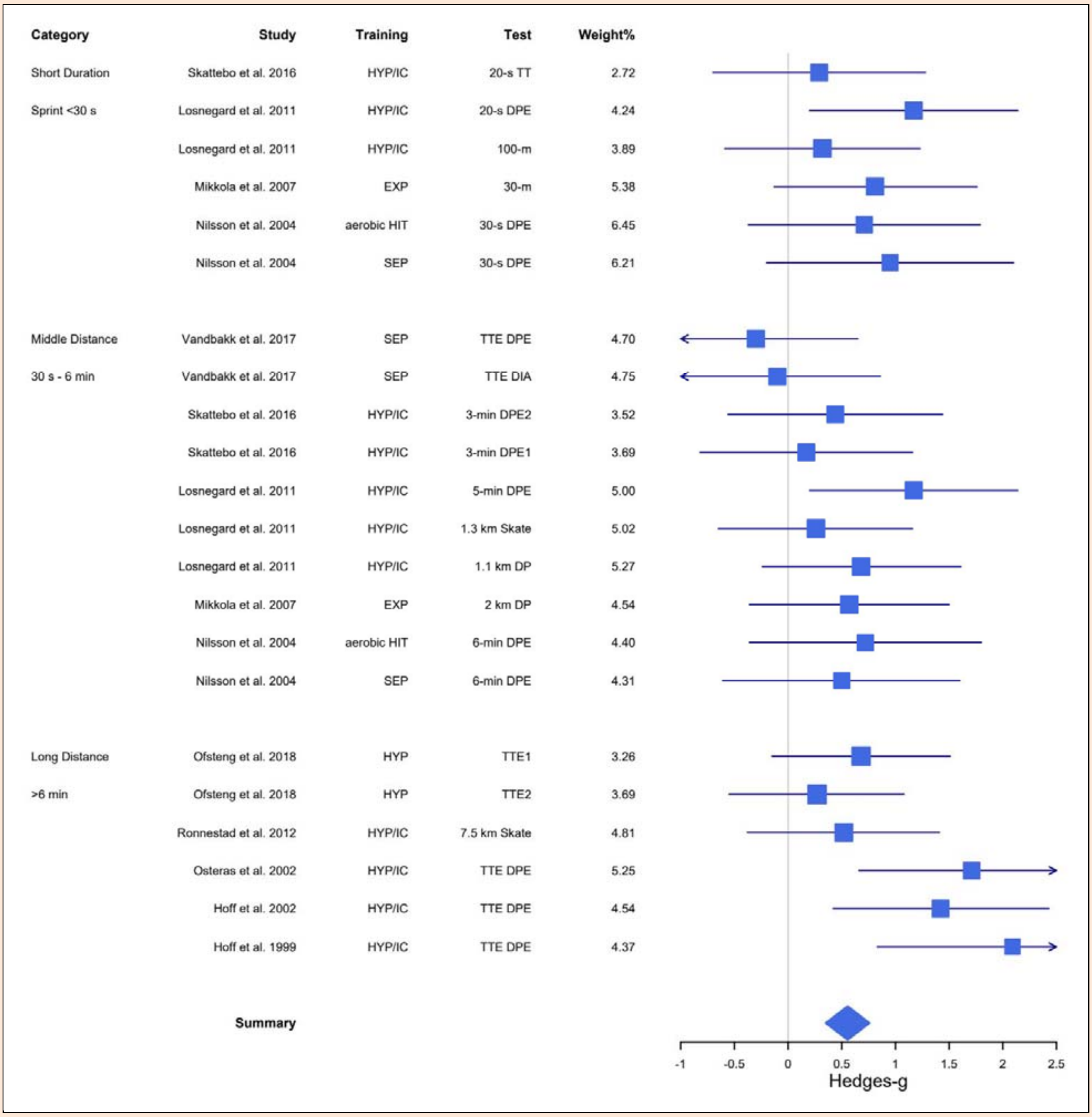

Figure 2. Forest plot of the effects of strength/power/speed training on XCS-specific performance. Positive values present effects in favour of the intervention group, while negative values present effects with respect to the pure endurance control group. The mean effect and its 95% confidence interval is presented as a diamond. HYP, strength training designed to increase muscle size; IC, heavy weight training designed to improve intramuscular coordination; SEP, training designed to enhance sprint endurance performance; EXP, explosive strength training; TT, time trial; DPE, double poling ergometer; TTE, time to exhaustion; DP, double poling.

Jump performance (squat jump and/or counter movement jump) improved in two studies (Paavolainen et al., 1991; Ronnestad et al., 2012) (8-11%, ES: 1.10-1.46), whereas another found no change in this respect in comparison to the control group (Losnegard et al., 2011). Assessment of the ability to produce force rapidly also produced mixed results, with improvements in the time required to produce submaximal forces (Hoff et al., 2002; Paavolainen et al., 1991) (22-30%, ES: 0.76-0.97) or in peak force at maximal aerobic velocity (Hoff et al., 1999). None of the articles reviewed focused on parameters related to muscle stiffness.

Body composition

Potential alterations in body mass during the period of intervention were examined in 7 of the 14 studies, with 6 observing no change in comparison to baseline (Hoff et al., 2002; Mikkola et al., 2007; Nesser et al., 2004; Ofsteng et al., 2018; Paavolainen et al., 1991; Ronnestad et al., 2012) and the other a significant increase in both the experimental and control groups following strength training (Skattebo et al., 2016). In one case the thickness of the *m. vastus lateralis* was monitored during the intervention, revealing a tendency towards a reduction in the control group and a relatively larger increase in the groups that performed strength training (Ronnestad et al., 2012). Similarly, the lean mass of the upper body was elevated, with no alteration in total body mass (Ofsteng et al., 2018). Other indices of body composition that exhibited no significant changes included skinfolds (Mikkola et al., 2007; Nesser et al., 2004; Paavolainen et al., 1991) and thigh and calf girth (Paavolainen et al., 1991); whereas Skattebo and colleagues (2016) reported a significantly larger enhancement in upper-arm circumference in the experimental (3.3%) than in the control group (2.0%) following 10 weeks of heavy strength training.

XCS performance

The effects of strength/power/speed training on XCS specific performance are presented in Figure 2. In two studies, sprint/speed performance was increased in the experimental group with no changes in the control group (Mikkola et al., 2007; Nilsson et al., 2004) (1.4 - 21%, ES: 0.71 - 1.05). Losnegard et al. (2011) reported only a trend towards an improvement in 100-m RS speed. In none of the studies were any other measures of anaerobic capacity improved.

In four studies XCS performance improved after the intervention, either in the experimental group alone (Losnegard et al., 2011; Nesser et al., 2004; Nilsson et al., 2004; Skattebo et al., 2016) or in both the experimental and control groups (Losnegard et al., 2011; Skattebo et al., 2016), with significantly greater improvement in the experimental group only in the study of Nilsson et al. (2004) (8-15%, ES: 0.50 - 0.72). In this same study the control group did not complete the XCS-specific roller skiing tests and race performance, making it impossible to calculate ES. The investigations in which no improvement was observed were all performed outside the laboratory and involved distances longer than 1 km (i.e., a 2-km RS DP time-trial on a flat indoor track (Mikkola et al., 2007), 1000 m of RS DP and 1.3 km of skating RS outdoors on an uphill road (Losnegard et al., 2011) or a 7.5-km RS time-trial outdoors (Ronnestad et al., 2012)).

In three instances DP performance was improved significantly by the intervention (Hoff et al., 2002; Hoff et al., 1999; Østerås et al., 2002) (56-137%, ES:1.42-2.09), whereas in other studies improvement occurred in both the experimental and control groups (Ofsteng et al., 2018) or in the control group only (Vandbakk et al., 2017).

The one study that examined XCS racing performance on-snow (Nesser et al., 2004) observed improvement during the winter/competition season following the intervention, with the group performing roller board improving more than those carrying out weight training (data provided only in the figure in this case). In general, the effect of strength/power/speed training on specific XCS performance can be evaluated as moderate (ES = 0.56, 95%CI: 0.35 - 0.76).

Physiological parameters

Maximal/peak oxygen uptake

Among the nine of the 12 studies that reported VO_{2max} values before and after the intervention, seven found no statistically significant change, while the two others (Losnegard et al., 2011; Vandbakk et al., 2017) documented increases during ski-skating and diagonal skiing, respectively, in comparison to the control group (7-9%, ES: 0.75-3.29). VO_{2peak} values while performing DP were reported in seven of the articles (Hoff et al., 2002; Hoff et al., 1999; Nilsson et al., 2004; Ofsteng et al., 2018; Østerås et al., 2002; Skattebo et al., 2016; Vandbakk et al., 2017).

Of the seven studies that found no differences between groups, two observed enhanced VO_{2peak} during DP in both groups (Skattebo et al., 2016; Vandbakk et al., 2017). Nilsson and colleagues (2004) showed elevated VO_{2peak} DP in the group performing 180-s intervals, but not among those performing 20-s intervals with a focus on strength/power.

None of the articles provided data concerning velocity or power output at $VO_{2max/peak}$.

Work economy/efficiency/gross efficiency

Work economy/gross efficiency was assessed in all but two (Nesser et al., 2004; Paavolainen et al., 1991) of the studies (Table 3). Statistically significant improvements (7 - 56%, ES: 0.52 - 1.75) in this parameter with at least one workload were documented in six articles (Hoff et al., 2002; Hoff et al., 1999; Mikkola et al., 2007; Nilsson et al., 2004; Østerås et al., 2002; Skattebo et al., 2016), whereas others observed no improvement in work economy (Losnegard et al., 2011; Ronnestad et al., 2012; Skattebo et al., 2016; Vandbakk et al., 2017) in comparison to a control group.

Blood lactate response

The levels of lactate in the blood at fixed workloads/velocities were measured in 6 studies (Hoff et al., 1999; Losnegard et al., 2011; Nilsson et al., 2004; Ofsteng et al., 2018; Paavolainen et al., 1991; Ronnestad et al., 2012); velocity at fixed concentrations of blood levels of lactate (2-4 $mmol \cdot L^{-1}$) assessed in one (Paavolainen et al., 1991); and velocity until this concentration had risen more than 1.5 $mmol \cdot L^{-1}$ above the resting level in another (Nilsson et al., 2004). The modes of exercise in these investigations were ski-walking (Mikkola et al., 2007; Paavolainen et al., 1991), running (Hoff et al., 1999), DP on an ergometer (Hoff et al., 1999; Nilsson et al., 2004; Østerås et al., 2002), DP on a treadmill (Ofsteng et al., 2018; Vandbakk et al., 2017), and Gear 2 skating on a treadmill (Losnegard et al., 2011). In none of the seven studies including these measurements was the blood level of lactate lower in the experimental than the control group.

Biomechanical parameters

In the case of DP, the various strength/power training interventions resulted in unchanged (Hoff et al., 1999; Losnegard et al., 2011; Østerås et al., 2002; Skattebo et al., 2016; Vandbakk et al., 2017) or higher poling frequency (in a 6-min test following 20-s interval training (Nilsson et al., 2004)), as well as in an unaltered cycle rate (Ofsteng et al., 2018; Vandbakk et al., 2017).

Table 3. **Summary of the findings reported in the studies included in our meta-analysis.**

				Maximal performance			Submaximal performance		
Study	**Parameters examined**	**Strength/power**	**Body composition**	**$VO_{2max/peak}$**	**Time trial**	**TTE, $vVO_{2max/peak}$, PPO, V_{max}**	**Blood lactate (AeT; AnT), anaerobic capacity**	**Eco/Eff/ Gross eff**	**Biomechanics (kinetics, kinematics, EMG)**
Paavolainen et al. 1993	Anthropometrics (body mass and height); % body fat and fat-free mass estimated from skinfold thickness; calf, thigh and arm girth; SJ and CMJ; maximal isometric force (ISO max) and various force-time parameters of the leg extensor muscles; AnT and VO_{2max} while ski-walking on a treadmill.	ISO max leg: ND EXP: Time to produce submaximal force at 60% of ISO max: ⇓ 28% [ES = 0.76; P<0.05] SJ: ⇑ 11.3% [ES=1.46; P<0.01] CMJ: ⇑ 8.2% [ES=1.34; P<0.01] CON: ND	BM; Fat (%), fat-free mass; calf, thigh and arm girth: ND	VO_{2max} ND	-	-	AeT ND AnT ND	-	-
Hoff et al. 1999	1RM sitting cable pull-down; AnT and VO_{2max} RUN; AnT and VO_{2peak} DP_ergo; cost of poling and TTE DP_ergo; body mass, blood levels of Hb and HCT	EXP: 1RM sitting cable pull-down: ⇑ 14.5% [ES=0.85; P<0.001] Peak force at 1RM: ⇑ 36.1%, [ES=9.39; P<0.05] Time to peak force at 80% 1RM: ⇓ 29.7% [ES=0.92; P<0.05] Time to peak force at 60% 1RM: ⇓ 22.4% [ES=0.97; P<0.05] Time to peak force during DPE: ⇓ 27% [ES=0.86; P<0.01] CON: ND	ND in BM	VO_{2peak} DPE, ND	-	STR: TTE_DPE: ⇑ 137% [ES=2.09; P<0.001]; PO DPE: ⇑ 26% [ES=7.22; P<0.05] CON: TTE DPE: ⇑ 58% [P<0.01]	AnT ND	STR: DPE economy ⇑ 32.5% [ES=1.75; P<0.05] CON: ND	STR: force in %1RM during DPE: ⇓ 34.8% [ES=0.88, P<0.05] CON: ND Poling frequency ND
Hoff et al. 2002	Body mass; 1RM sitting cable pull-down; peak force, peak force last repetition, time-to-peak force, time-to-peak force (TPF)_last repetition; AnT and VO_{2max} RUN; AnT and VO_{2peak} DPE	EXP: 1RM: ⇑ 9.9% [ES=0.80; P<0.05]; Peak force at 60% and 80% 1RM: ⇑ 33-34% [ES=1.09-1.19; P<0.05]; TPF_last repetition: ⇓ 60% and 50% [ES=1.45; P<0.05] CON: Peak and time to peak force at 60% 1RM: [P<0.05]	ND in BM	ND in VO_{2max} (RUN) or VO_{2peak} DP in either of the two groups.	-	EXP: TTE_DPE: ⇑ 56% [ES=1.42; P<0.05] CON: TTE_DPE: ⇑ 25% [P<0.05]	ND	EXP: Work economy (cost of poling) during DP: ⇑ 56% [ES=1.44; P<0.05] CON: ND	-

I, intervention group; C, control group; AeT, aerobic threshold; AnT, anaerobic threshold; BLC, blood lactate concentration; CMJ, countermovement jump; DPE, double poling ergometer; ES, significant effect size for the group x time interaction when comparing the intervention and control groups; Hb, hemoglobin; HCT, hematocrit,; HRT, heavy resistance training; IT20-s: 20-s sprint interval training group; IT180-s 180-s sprint interval training group; ND; no difference; NM: Not measured; SIG, sprint interval group; SJ, squat jump; STR: strength training group; TT: time-trail; UB: upper body; WT, weight training

Table 3. Continue.

Study	Parameters examined	Maximal performance: Strength/power	Body composition	$VO_{2max/peak}$	Time trial	TTE, $vVO_{2max/peak}$, PPO, V_{max}	Submaximal performance: Blood lactate (AeT; AnT), anaerobic capacity	Eco/Eff/ Gross eff	Biomechanics (kinetics, kinematics, EMG)
Østerås et al. 2002	Body mass; 1RM sitting cable pull-down; peak force, peak force last repetition, time to peak force, time to peak force last repetition; AnT and VO_{2max} RUN; AnT and VO_{2peak} DPE; cost of poling and TTE_DPE	EXP: 1RM: ⇑ 22% [ES=2.18; P<0.05]; Relative strength: ⇑ 22% [ES=2.67; P<0.001] Peak power increased, except at the two lowest loads, with a shift in the force-power curve towards higher speeds and loads. CON: ND	ND in BM	VO_{2peak} DPE: ND	-	EXP: TTE_DPE: ⇑ 61% [ES=1.71; P<0.05] CON: TTE_DPE: ⇑ 21% [P<0.05]	Peak BLC, AnT: ND	EXP: Exercise DP economy: ⇑ 8.8%, [ES=1.23; P<0.01] CON: ND	Poling frequency: ND
Nilsson et al. 2004	DPE: power output during 30 s and 6 min; work efficiency (VO_2 at a given work load) and BLC at submax; VO_{2peak} DP; DP frequency; VO_{2max} RUN	-	-	IT180-s: VO_{2peak}: ⇑ 4.2% [ES=0.57; P<0.05] IT20-s & CON: ND	IT20-s: 30-s DPE performance (mean power): ⇑ 22% [ES=0.95; P<0.05] 6-min DPE performance (mean power): ⇑ 8% [ES=0.50; P<0.05] IT180-s:30-s DPE performance (mean power): ⇑ 17% [ES=0.71; P<0.05] 6-min DPE performance (mean power): ⇑ 15% [ES=0.72; P<0.05] C: ND	IT20-s: 30-s DPE peak power: ⇑ 21% [ES=1.05; P<0.05] IT180-s: 30-s DPE peak power: ⇑ 17% [ES=0.71; P<0.05] CON: ND	IT180-s: BLC_sub ⇓ 18% [ES=0.68, P<0.05] IT20-s & CON: ND	IT20-s: Work efficiency (VO_2 submax): ⇑ 9% [ES=0.66; P<0.05] IT180-s: Work efficiency (VO_2 submax): ⇑ 7% [ES=0.52; P<0.05] CON: ND	IT180-s: Mean 6-min poling force TT: ⇑ 11% [ES=0.43; P<0.05] IT20-s & CON: ND IT20-s: 6-min poling frequency TT: ⇑ 11% [ES=0.64; P<0.05] IT180-s & CON: ND

I, intervention group; C, control group; AeT, aerobic threshold; AnT, anaerobic threshold; BLC, blood lactate concentration; CMJ, countermovement jump; DPE, double poling ergometer; ES, significant effect size for the group x time interaction when comparing the intervention and control groups; Hb, hemoglobin; HCT, hematocrit,; HRT, heavy resistance training; IT20-s: 20-s sprint interval training group; IT180-s 180-s sprint interval training group; ND; no difference; NM: Not measured; SIG, sprint interval group; SJ, squat jump; STR: strength training group; TT: time-trail; UB: upper body; WT, weight training

Table 3. Continue.

					Maximal performance			Submaximal performance	
Study	**Parameters examined**	**Strength/power**	**Body composition**	**$VO_{2max/peak}$**	**Time trial**	**TTE, $vVO_{2max/peak}$, PPO, V_{max}**	**Blood lactate (AeT; AnT), anaerobic capacity**	**Eco/Eff/ Gross eff**	**Biomechanics (kinetics, kinematics, EMG)**
Nesser et al. 2004	Body weight and skinfold (%BF); UB power freestyle arm ergometer (TTE); UB strength Vasa Trainer (10RM); TT DP RS (total time); TT DP RS uphill; DP TT DP RS flat; race results	RB: UB power: ⇑ 0.29W/kg [ES=5.59; P<0.05] UB strength: ⇑ 0.99J/kg [ES=5.23; P<0.05] SS & WT & & CC & C: ND	ND in body mass, body height, % body fat.	-	RB: TT total: ⇓ 36 s [ES=3.04; P<0.05] TT uphill: ⇓ 22 s [ES=2.88; P<0.05] TT_flat: ⇓ 14 s [ES=1.59; P<0.05] SS & WT & Cir & C: ND All groups improved race performance. RB > Cir, SS and W, Cir > WT. Changes were inversely related to changes in relative UBS and UBP, as well as in TT DP RS.	-	-	-	-
Mikkola et al. 2007	Anthropometrics: body mass, height, % body fat (estimated from skinfold thickness); calf and thigh girth; maximal isometric force (ISO max) and various force-time parameters of the leg extensor muscles; bilateral maximal dynamic force of leg extensor muscles; maximal isometric force of trunk flexors and extensors; EMG leg extensors during strength test; AnT and VO_{2max} while ski-walking on a treadmill; 30-m DP RS test ($V30_{DP}$) with 20-m flying start on an indoor track; Maximal Anaerobic Skiing Test (MAST; 9-10x150m Rest: 100 s); DP work economy; maximal 2000-m DP test (mean velocity = V_{2K}); VO_{2peak} DP	I & C: Maximal isometric force of the leg extensors: both ⇑6%, P<0.05. I: absolute forces in earlier portion (0-100 ms) of force-time curve: ⇑ 18%, ES=1.35, P<0.05 IEMG m. *vastus lateralis* in early portion of isometric action (0-100 ms) ⇑ 21%, ES=1.65, P<0.05 IEMG m. *vastus medialis* in early portion of isometric action (0-100ms) ⇑ 27%, ES=1.39, P<0.05 C: ND	-	No significant changes in VO_{2max} in either I or C	I: ND C: V_{2K} ⇑ 2.9% [P<0.01]	I: V30DP ⇑ 1.4% [ES=0.81; P<0.05] C: ND	-	I: improved sport-specific DP economy during the 2-km test: VO2: ⇓ 7% [P<0.05] C: ND	-

I, intervention group; C, control group; AeT, aerobic threshold; AnT, anaerobic threshold; BLC, blood lactate concentration; CMJ, countermovement jump; DPE, double poling ergometer; ES, significant effect size for the group x time interaction when comparing the intervention and control groups; Hb, hemoglobin; HCT, hematocrit,; HRT, heavy resistance training; IT20-s: 20-s sprint interval training group; IT180-s 180-s sprint interval training group; ND; no difference; NM: Not measured; SIG, sprint interval group; SJ, squat jump; STR: strength training group; TT: time-trail; UB: upper body; WT, weight training

Table 3. Continue.

Study	Parameters examined	Maximal performance: Strength/power	Body composition	$VO_{2max/peak}$	Time trial	TTE, $vVO_{2max/peak}$, PPO, V_{max}	Submaximal performance: Blood lactate (AeT; AnT), anaerobic capacity	Eco/Eff/ Gross eff	Biomechanics (kinetics, kinematics, EMG)
Losnegard et al. 2011	1RM seated pull-down and half squat; CSA of m. *triceps brachii* and *quadriceps*; VO_{2max} during RUN and RS skate. Energy consumption at submaximal RS intensities; DP performance (20-s and 5-min) on a DPE; DP and Skate RS TT (DP 1.1 km and Skate 1.3 km); 100-m DP; Counter movement jump (CMJ) performance.	I: 1RM seated pull-down: ⇑19% [ES=5.74; P<0.01] 1RM half squat: ⇑12%, [ES=6.81; P<0.01] C: ND	No difference between groups in UB LBM. I in UB LBM increased by 3%, P<0.05 C: ND Total body weight was unchanged in both groups.	I: VO_{2max} skate: ⇑ 7% [ES=3.29; P<0.01] C: ND VO_{2max} RUN: ND	1.1-km DP performance (DPE):I: ⇑ 7.4% [ES=0.68; P<0.05] C: ⇑ 6.0% [ES=5.74; P<0.05] 1.3-km Skate RS performance: I: ⇑ 3.7%, [ES=0.26; P=0.14] C: ⇑ 3.3% [P<0.05]	I: 100-m RS Sprint: ⇑ 1.3% [P=0.1] C: ND I & CON: 20-s power output with DP: ⇑ 8.3% vs. ⇑ 6.2% [both P<0.001]	No group differences with respect to BLa, or HR during submaximal RS	No group differences with respect to VO_2 during submaximal RS I: RER submaxi-mal stages: ⇓ 4.4-5.5% [P<0.05] C: ND	Poling frequency: ND CMJ: Trend towards decrease in C with no change in I
Rønnestad et al. 2012	Architectural changes of m. *vastus lateralis*, 1RM deep squat and seated pull-down, squat jump (SJ), VO_{2max}, work economy Skate RS, and 7.5-km TT RS.	I: 1RM deep squat: ⇑12% [ES=2.9; P<0.01] 1RM seated pull-down: ⇑23% [ES=1.5; P<0.01] SJ: ⇑8.8% [ES=1.1; P<0.05] C: ND	No changes in total body mass.	No change in VO_{2max} skate RS	No changes in 7.5-km TT RS performance.	-	No change in BLC during submaximal RS.	No group difference in work economy.	-
Skattebo et al. 2016	Seated pull-down 1RM; Upper arm circumference; VO_{2max} RUN; Submaximal O_2-cost; VO_{2peak} DP; 20-s DPE performance; 3-min DPE performance (rested: sprint-test and fatigued: finishing-test).	Seated pull-down 1RM increased more in I (24%) [*P*<0.01] than C (8%) [P<0.05], with a group difference of 15% [ES=0.90; P<0.01]. Upper arm circumfer-ence increased more in I (3.3%) [P<0.001] than C (2%) [P<0.05] with a group difference of 1.3% [ES=0.18; P=0.05].	Body weight increased in both I (2.5%, P<0.01) and C (2.6%, P<0.05), with no group difference.	Absolute VO_{2max} RUN was unchanged in both groups, while the relative values were reduced in I (−3.7%) but unchanged in C. Absolute VO_{2peak} DP increased both in I (2.9%, P<0.1) and C (7.7%, P<0.1), whereas the relative values were unchanged.	No differences in DP performance tests.	Average power output increased by 17.1% in I and 16.2% in C (3-min TT DP sprint test) and 14.9% vs. 13.1% (3-min TT DP finishing- test) with no group differences.	-	Submaximal O_2-cost demonstrated similar changes or were un-changed in both groups.	Poling frequency: ND

I, intervention group; C, control group; AeT, aerobic threshold; AnT, anaerobic threshold; BLC, blood lactate concentration; CMJ, countermovement jump; DPE, double poling ergometer; ES, significant effect size for the group x time interaction when comparing the intervention and control groups; Hb, hemoglobin; HCT, hematocrit,; HRT, heavy resistance training; IT20-s: 20-s sprint interval training group; IT180-s 180-s sprint interval training group; ND; no difference; NM: Not measured; SIG, sprint interval group; SJ, squat jump; STR: strength training group; TT: time-trail; UB: upper body; WT, weight training

Table 3. Continue.

Study	Parameters examined	Strength/power	Body composition	$VO_{2max/peak}$	Time trial	TTE, $vVO_{2max/peak}$, PPO, V_{max}	Blood lactate (AeT; AnT), anaerobic capacity	Eco/Eff/ Gross eff	Biomechanics (kinetics, kinematics, EMG)
		Maximal performance					Submaximal performance		
Vandbakk et al. 2017	Physiological (VO_{2peak}) and kinematic (cycle length and rate) responses during submaximal and maximal diagonal and DP treadmill RS incl. peak treadmill speed; sitting poling-specific maximal UB strength (1RM) and average power at 40% 1RM (P40) at maximal speed.	I: 1RM ⇑ 18% [ES=1.20; P<0.035]; P40 ⇑ 20% [ES=1.06; P=0.057] C: 1RM ⇑ 10% [P<0.035]; P40 ⇑ 14% [P=0.057]	ND in BM	I: VO_{2max} DIA (L/min): ⇑ 9% [ES=0.75; P<0.05] VO_{2max} DP: ⇑ 10% [ES=0.47; P>0.05] C: VO_{2max} DIA (L/min): ND VO_{2max} DP: ⇑ 6% [P<0.05]	-	TTE DIA: No within- or between-group differences TTE DP: ⇑ 18% [P<0.01 in CON only]	-	No change in oxygen cost while skiing with DP or DIA at submaximal intensities	No changes in cycle length and rate during DP and DIA
Øfsteng et al. 2018	1RM in UB exercises; work economy; TTE (Test 1) and TTE after a prolonged test (Test 2); neural activation; oxygen saturation in muscle; DP kinematics during prolonged submaximal DP RS followed directly by a TTE-test (Test 2). The difference TTE_Test1 – Test 2 (i.e., TTEdiff) aimed to reflect the skier's ability to maintain DP performance after prolonged exercise. As vibration did not induce any additional effect on strength or endurance gains, values for the two strength training groups were here pooled (STR).	STR: 1RM seated pull down: ⇑ 8.9% [ES=1.90; P=0.023] 1RM triceps press: ⇑ 21.7% [ES=1.78; P<0.01] C: ND	ND in BM STR: UB LBM: ⇑ 2.8% [P =0.006]	VO_{2peak} DP: ND	-	STR: TTE (Test 1): ⇑ 9.6% [ES=0.27; P=0.55] TTE (Test 2): ⇑ 19.6% [ES=0.68; P=0.07] Post-test TTEdiff was significantly reduced compared to C (-0.45 min vs. -1.32 min) C: TTE (Test 1): ⇑ 7.6% TTE (Test 2): ⇑ 8.8%	In both STR and C post-PO at 4 mmol L^{-1} was higher than the pre-test value	Both STR and C reduced VO_2-consumption at 10 km and 12 km/h. Physiological response during prolonged submax DP: ND EXP reduced RPE during final 20 min	EMG and kinematics: ND

I, intervention group; C, control group; AeT, aerobic threshold; AnT, anaerobic threshold; BLC, blood lactate concentration; CMJ, countermovement jump; DPE, double poling ergometer; ES, significant effect size for the group x time interaction when comparing the intervention and control groups; Hb, hemoglobin; HCT, hematocrit,; HRT, heavy resistance training; IT20-s: 20-s sprint interval training group; IT180-s 180-s sprint interval training group; ND; no difference; NM: Not measured; SIG, sprint interval group; SJ, squat jump; STR: strength training group; TT: time-trail; UB: upper body; WT, weight training

Discussion

This systematic review aimed to identify and evaluate the current scientific literature concerning the influence of strength, power and speed training on relevant physiological and biomechanical characteristics and performance of competitive XC skiers. The findings presented demonstrate that such training not only improves strength and power *per se*, but is also beneficial for several other key determinants of XCS performance. However, the conclusions drawn are inconsistent, perhaps due to methodological differences and/or the varying characteristics of the participants. In general, the methodological quality of the articles examined was poor-to-fair (PEDro scores of 3 - 7), being good in only two cases.

Training programs

All interventions evaluated ranged from 6 - 12 weeks in length (mostly 6 - 8 weeks), with 2 or 3 sessions of strength training each week. In no case was the persistence of the effects obtained assessed. Therefore, at present our knowledge concerning neuro-muscular and/or structural adaptations of XC skiers to strength training is based on relatively short-term interventions without follow-up, whereas the potential beneficial effects on the complex movements involved in this sport might be achieved only after longer programs of strength training (e.g., at least 24 weeks (Berryman and coworkers (2018)).

All of the interventions took place either during the preparatory or pre-competition period (e.g., October-November). Since none involved the 5-month period of competition (beginning of November to beginning of April), comparison of the potential effects of no, less or more strength training on actual strength and performance during this period remains to be carried out. Although Sandbakk (2018) did state that at least one session of strength training per week is required, in the case of XCS this proposal is not based on scientific evidence.

Of the articles analyzed, 67% involved heavy strength training, an observation consistent with findings that elite XC skiers utilize training of this nature to enhance the maximal strength and power of muscles involved specifically in skiing (Sandbakk, 2018). Surprisingly, only five interventions involved the use of free weights, Olympic lifts and/or powerlifting (Losnegard et al., 2011; Mikkola et al., 2007; Nesser et al., 2004; Paavolainen et al., 1991; Ronnestad et al., 2012), even though these types of strength training have been shown to be highly effective, even in young athletes (Granacher et al., 2016).

XCS involves extensive use of the muscles of both the upper and lower body. However, although all 12 studies involved training of upper-body muscles, only four included strength training of the legs (Losnegard et al., 2011; Mikkola et al., 2007; Paavolainen et al., 1991; Ronnestad et al., 2012), despite their major role in generating propulsive force in connection with most of the sub-techniques (Komi, 1987; Stöggl and Holmberg, 2015; Vahasoyrinki et al., 2008). This situation may reflect the belief by athletes and coaches that strength training of the legs requires longer overall recovery than training the upper body (personal communication). Apparently, the best approach to optimizing the strength and power of the legs without interfering with overall recovery remains to be determined.

At the same time, only two studies involved exercises designed to strengthen the core muscles (Mikkola et al., 2007; Nesser et al., 2004), which are utilized extensively in all XCS sub-techniques, and neither of these studies employed application of heavier loads. Nor was core strength analyzed or reported specifically in any case.

However, two studies, neither of which included a control group, did focus on strengthening the trunk. Therell and colleagues (2021) found that supplemental dynamic and static training of core strength exerted no effect on the energetic cost of XCS at submaximal speeds. In addition, Carlsson et al. (2017) reported that strength training (including core exercises) increased VO_{2max}, peak roller skiing speed and upper-body strength to the same extent as training on a ski-ergometer. Thus, at present, there is little evidence that systematic core training is beneficial to sport-specific performance (Faigenbaum et al., 2016), although elite skiers appear to be convinced that this is the case (Sandbakk, 2018; Sandbakk and Holmberg, 2017; Solli et al., 2017). The best approach to strengthening the core muscles of XC skiers remains to be elucidated.

Several of the investigations involved only 1-3 different types of strength exercises (e.g., seated poling only (Hoff et al., 2002; Hoff et al., 1999; Østerås et al., 2002) or seated and standing poling together with triceps extension (Ofsteng et al., 2018; Skattebo et al., 2016) or squats (Losnegard et al., 2011; Ronnestad et al., 2012)). In several cases the poling motion characteristic of many sub-techniques of XCS was simulated utilizing a cable pulley (either while seated or standing) (Hoff et al., 2002; Hoff et al., 1999; Losnegard et al., 2011; Ofsteng et al., 2018; Østerås et al., 2002; Ronnestad et al., 2012; Skattebo et al., 2016), a DP ergometer (Nilsson et al., 2004) or a roller-board (Nesser et al., 2004; Vandbakk et al., 2017). In light of recommendations that the strength training of XC skiers should focus on relevant muscles and movements (Losnegard, 2019), it is questionable whether more complex exercises involving more degrees of freedom of movement actually load muscles maximally and thereby provide sufficient stimulus to improve strength and power optimally. Clearly, in this context the considerable freedom of movement during XCS, with complex coordination between the upper and lower body and interactions between the skier, his/her equipment and the ground/snow, should be given special consideration.

Effects on strength and power output

As expected, most of the interventions led to moderate-to-large improvement (6-24%) in parameters that reflect strength and power (Hoff et al., 2002; Hoff et al., 1999; Losnegard et al., 2011; Mikkola et al., 2007; Nesser et al., 2004; Nilsson et al., 2004; Ofsteng et al., 2018; Østerås et al., 2002; Paavolainen et al., 1991; Ronnestad et al., 2012; Skattebo et al., 2016; Vandbakk et al., 2017). Obviously, the type of training and nature of the exercises utilized to test its effects, both of which varied widely, can exert an impact on the extent of improvement in both strength and neuromuscular adaptations observed. In several cases, the same exercises employed during the intervention were utilized, at least in part, to monitor effects on strength and power (Hoff et al., 2002; Hoff et al., 1999; Losnegard et al., 2011; Nilsson et al., 2004; Ofsteng et al., 2018; Østerås et al., 2002; Ronnestad et al., 2012; Skattebo et al., 2016), whereas in others these two types of exercise differed (Mikkola et al., 2007; Nesser et al., 2004; Paavolainen et al., 1991; Vandbakk et al., 2017).

In many cases, the reliability and validity of the procedures employed to test strength/power and XCS performance had not been and/or were not assessed. In only two studies (Losnegard et al., 2011; Skattebo et al., 2016) was the correlation between strength and XCS-specific performance prior to the intervention determined. Skattebo and colleagues (2016) reported moderate relationships between 1RM seated pull-down and short-term DP performance. Similar correlations were observed by Losnegard and colleagues (2011) for women and men combined, but when the sexes were analyzed separately, such correlations were seen primarily in the case of the women and these were much lower or even trivial.

In a correlative study, Stöggl and colleagues (2011) reported a positive correlation between maximal bench press, bench pull (1RM and power output at submaximal loads) and squat jump performance with peak velocity in the G3, DP and diagonal skiing sub-techniques. Among the interventions reviewed, only two involved bench press (Mikkola et al., 2007; Nesser et al., 2004), although most included a pull exercise other than bench pull, and only three utilized jumping exercises (Mikkola et al., 2007; Nesser et al., 2004; Paavolainen et al., 1991). Moreover, in most of the testing protocols, force was assessed only at low (1RM) or high velocities (i.e., jumps), whereas to evaluate the effects of a strength intervention reliably, this parameter should be determined at a range of different velocities. For example, Stöggl and colleagues (2011) found that power output at submaximal speeds was more closely associated with XCS sprint performance than the 1RM.

Effects on body composition

In the interventions reviewed here, short-term training improved strength/power without altering body composition (i.e., body mass, fat mass, lean mass) and with significant (Skattebo et al., 2016) or no effect (Paavolainen et al., 1991) on muscle circumference. The potential lack of muscle hypertrophy (not measured directly in any of the articles examined) might have been due to the short duration of the interventions, insufficient stimulus and/or nutrition, interference by parallel endurance training (Bell et al., 2000; Kraemer et al., 1995), and/or primary neuromuscular adaptations. These factors should be taken into consideration if a skier desires to both enhance strength and increase lean mass during a certain period. It is noteworthy that only six of the 12 studies involved women and only two involved junior skiers, both groups for whom strength training is considered to be essential for attaining an athletic physique (Stöggl et al., 2019).

Physiological capacities

Maximal /Peak oxygen uptake

A number of investigations on endurance athletes have shown that neither VO_{2max} nor the fractional utilization of VO_{2max} (e.g., performance VO_2) are altered by heavy strength training (e.g. Ronnestad et al., 2012; Saunders et al., 2004; Skattebo et al., 2016). Of the nine studies here in which VO_{2max} (pre/post) was reported, six observed no change (Hoff et al., 2002; Losnegard et al., 2011; Mikkola et al., 2007; Nilsson et al., 2004; Paavolainen et al., 1991; Skattebo et al., 2016); whereas Losnegard and colleagues (2011) observed an elevation in VO_{2max} in connection with the G2 skating technique (although unchanged while running) and Vandbakk and co-workers (2017) an increase in the case of diagonal skiing, both of which sub-techniques involve utilization of the entire body.

Indeed, a unique aspect of XCS are its different sub-techniques involving usage of upper- and lower-body muscles to different extents. One factor that limits VO_{2peak} is the amount of muscle mass involved (Calbet and Joyner, 2010; Saltin, 1985) and the VO_{2peak} of many XC skiers is 3 – 10% lower while utilizing DP than DIA (see the reference list in Stöggl et al., 2019). Accordingly, VO_{2peak} might be improved by involving more muscle mass in the sub-techniques (for example, by modifying the DP technique (Holmberg et al., 2006) or, alternatively, by enhancing muscle mass through strength training. In this context, since the 1960´s, upper-body capacity while performing arm cranking and double poling has risen from approximately 70% to 95% of VO_{2max}, a development that can be attributed to more well-trained upper-body musculature (Saltin, 1997; Stöggl et al., 2019).

Of the nine investigations examined here that monitored VO_{2peak} during DP, two reported that this parameter improved after the intervention; but since it improved to the same extent in the control group, this change could not be attributed to the strength intervention *per se* (Skattebo et al., 2016; Vandbakk et al., 2017). Therefore, at present there is little evidence that strength training of the upper body enhances VO_{2peak} during DP, but it must always be remembered that all relevant studies reported to date have been short-term.

Work economy/efficiency

At any given velocity, work economy is determined by a complex interplay between a variety of physiological and biomechanical factors. Unfortunately, despite the convincing positive effects of strength training on work economy in connection with several other endurance sports (Beattie et al., 2014; Berryman et al., 2018), the findings with respect to XCS are not yet as convincing. Of the 10 articles analyzed here that assessed work economy/gross efficiency before and after the intervention, four observed no change (Losnegard et al., 2011; Ronnestad et al., 2012; Skattebo et al., 2016; Vandbakk et al., 2017), five a lowered oxygen cost (Hoff et al., 2002; Hoff et al., 1999; Mikkola et al., 2007; Nilsson et al., 2004; Østerås et al., 2002) and one similar changes in the intervention and control groups (Ofsteng et al., 2018). Furthermore, the findings of Hoff and colleagues (2002; 1999) have been questioned on the basis of their unconventional approach to measuring work economy (Losnegard et al., 2011; Skattebo et al., 2016).

Interestingly, Nilsson and colleagues (2004) utilized training that involved 20-s maximal sprints in combination with explosive DP movements designed to stimulate the stretch-shortening cycle of upper-body muscles involved in propulsion. Such stimulation has been reported to enhance both skiing speed and performance while executing several XCS sub-techniques (Lindinger et al., 2009a; Lindinger et al., 2009b). This type of training stiffens the muscle-tendon system, which might allow more efficient storage and utilization of elastic energy at this level, resulting in shorter contact with the ground and less expenditure of energy (Anderson, 1996; Cavagna et al., 1964; Cavanagh and Kram, 1985; Hakkinen et al., 1985; Spurrs et al., 2003).

While the exact mechanism(s) underlying the improvement in work economy evoked by strength training remains unclear, better neuromuscular function almost certainly plays a role in this context. Altogether, the discrepancies in the findings concerning work economy in the interventions reviewed here may be due to differences regarding duration and the nature of the strength training, as well as in the methodology utilized for assessment, and/or the relatively small numbers of subjects.

Blood lactate

To date, findings on the effects of strength training on performance at the lactate threshold are somewhat inconclusive. In the investigations analyzed here, where many different types of exercise were employed (including ski-walking, performing DP on an ergometer or treadmill, and G2 skating on a treadmill), the blood level of lactate associated with submaximal and maximal workloads either did not change (Hoff et al., 2002; Hoff et al., 1999; Losnegard et al., 2011; Østerås et al., 2002; Paavolainen et al., 1991; Ronnestad et al., 2012), decreased only in the group whose training involved 180-second sessions of DP (Nilsson et al., 2004) or was altered to the same extent in both the intervention and control groups (Ofsteng et al., 2018).

Effects on XCS performance

Time-trials of short duration (< 30 s)

Two of the reports (Mikkola et al., 2007; Nilsson et al., 2004) describe moderate-to-high (1.4 - 5.0%) effects of strength training on short-term DP performance, whereas two others (Losnegard et al., 2011; Skattebo et al., 2016) observed a trend towards similar improvement in both their experimental and control groups. In light of the enhanced importance of rapid acceleration and subsequent maintenance of high-speed during sprint and mass-start races, strength training may be especially beneficial for skiers whose maximal speed is slower. At the same time, in this context conventional speed or sprint training (e.g., sprint-interval training) or a combination of both strength and speed training might be at least as effective as strength training alone (Kristoffersen et al., 2019; Sleivert et al., 1995), although this possibility remains to be explored.

Time-trials of intermediate duration (30 s-6 min)

Several of the studies tested performance employing 3-6 min time-trials and/or an actual XCS sprint competition 1-2 km in length (Losnegard et al., 2011; Mikkola et al., 2007; Nilsson et al., 2004; Skattebo et al., 2016). The results obtained are somewhat contradictory, including improvements in the performance of the control group only (Mikkola et al., 2007), similar improvements in both the intervention and control groups (Losnegard et al., 2011; Skattebo et al., 2016) and more pronounced improvement following "muscular endurance" than simple endurance training (although without a control group in this case) (Borve et al., 2017). Therefore, at present, no definitive conclusions concerning the effects of strength training on time-trial performance under conditions of actual "sprint competition" can be drawn. In light of the considerable demands on strength and speed placed by modern XCS sprint techniques (Pellegrini et al., 2018), this situation is surprising and further investigation is clearly warranted. In addition, findings of similar improvements in the intervention and control groups in certain of the studies might reflect either learning effects or simply the expected consequence of training in general.

Time-trials of longer duration (>6 min) and time-to-exhaustion testing

At present, the potential benefits of strength training for XC skiers competing over longer distances (e.g., 5 - 50 km) have yet to be demonstrated definitively. Although performance in XCS sprints (e.g., 2 - 4 min in duration) and longer races are correlated (Stöggl and Stöggl, 2013), the positive effects of strength training on the latter are not as clear. For instance, of the articles reviewed here, only one analyzed competitive performance, concluding that training strength (3-12 RM) on an inclined roller-board improves distance XCS performance on-snow (Nesser et al., 2004). However, in this case the participants were non-competitive junior XC skiers and there was no control group with respect to competitive performance. Rønnestad and colleagues (2012) found that strength training by Nordic Combined athletes did not enhance their performance while using a freely chosen skating technique during a 7.5-km time-trial on a roller skiing track.

In all of the other relevant studies, XCS performance of longer duration was assessed on the basis of time-to-exhaustion tests utilizing roller skis or DP ergometers. Since no performance on-snow was analyzed, the external validity of these results is moderate. For example, Hoff (1999), Hoff (2002) and Østerås (2002) and coworkers found that heavy strength training improved time-to-exhaustion on a DP ergometer considerably (57 - 137%); whereas Rønnestad and colleagues (2012) detected little or no effect of such training on 7.5-km roller skiing performance, as mentioned above. Thus, improvement in connection with open-ended time-to-exhaustion tests was more pronounced than during time-trials.

Biomechanical aspects

Two cross-sectional studies have demonstrated that when competitive skiers are performing DP (Stöggl et al., 2011; Sunde et al., 2019), diagonal skiing or V2 (Gear 3) skating (Stöggl et al., 2011), higher general strength is associated with more poling force and slower cycles. However, surprisingly few scientific investigations have focused on the effects of strength training on various biomechanical parameters related to XCS performance. Most of the studies reviewed here that included biomechanical analyses (7/12) focused simply on cycle characteristics (gross kinematics). Cycle length, analyzed in two studies only, was unaffected by the strength training intervention (Ofsteng et al., 2018; Vandbakk et al., 2017). Since longer cycles are linked to peak XCS speed (Stöggl and Holmberg, 2011; Stöggl and Müller, 2009), it is surprising that current findings indicate that the type of strength training employed did not influence XCS technique.

With respect to kinetics, one study demonstrated that strength training reduced time-to-peak force by 27% and relative peak poling force by 35%, with no change in the absolute level of peak pole force as assessed on a DP ergometer (Hoff et al., 1999). In contrast, Nilsson and colleagues (2004) documented a 22% elevation in peak power following 6 weeks (3 sessions each week) of training involving 180-s intervals of DP.

In the only intervention in which muscle activation was monitored, aspects of the EMG pattern related to the magnitude of such activation did not change (Ofsteng et al., 2018). The effects of strength or speed training on temporal parameters related to muscle activity, such as the sequence in which muscles become involved, have yet to be examined.

In any case, why are the biomechanics of XCS technique and XCS performance not influenced by an increase in general strength? This observation is particularly interesting in the light of the relatively large number of correlative cross-sectional articles that have documented an association between the strength *per se* and performance of a XC skier (Alsobrook and Heil, 2009; Bolger et al., 2015; Haymes and Dickinson, 1980; Heil et al., 2004; Holmberg and Nilsson, 2008; Mende et al., 2019; Mikkola et al., 2010; Ng et al., 1988; Niinimaa et al., 1978; Sagelv et al., 2018; Sandbakk et al., 2011; Sandbakk et al., 2015; Sandbakk et al., 2014; Sjokvist et al., 2015; Stöggl et al., 2015; Stöggl et al., 2011; Stöggl et al., 2010a; Stöggl et al., 2007; Wiltmann et al., 2016). Furthermore, modern XCS requires considerable strength and power for the efficient production and transfer of forces.

In this context, several sub-techniques of XCS (including DP, the running diagonal stride or Klaebo style (Pellegrini et al., 2018), jumping V1 (G2) and double-push (Stöggl and Holmberg, 2015; Stöggl et al., 2010b; Stöggl et al., 2008)) have become considerably more dynamic in recent decades. Recent measurements of peak pole forces (Stöggl and Holmberg, 2011; Stöggl and Holmberg, 2016; Stöggl et al., 2018) have revealed values approximately 150% higher than those reported a decade ago (Holmberg et al. 2005), with a concomitant elevation in cycle length by as much as 75% (Stöggl and Müller, 2009). There are indications that less muscle activation, slower cycles with more swing time, and a longer time-to-peak pole force during DP skiing allow more pronounced extraction of O_2 and better performance (Björklund et al., 2015; Stöggl et al., 2013).

Furthermore, higher skiing speeds are associated with shorter ground contacts (<250 ms), which are, in fact, similar in duration to those associated with various forms of jumping and sprinting exercise (Stöggl et al., 2011; Stöggl and Müller, 2009). Clearly, the ability to develop greater force more rapidly has become crucial to the successful utilization of many modern XCS techniques. However, the strength training studies presented here reflect no clear changes as a result of these developments.

In this context, one potential limitation of these studies is that biomechanical parameters related to pole and leg kinetics were not analyzed. Very few studies have analyzed biomechanical factors under actual XCS conditions and, indeed, there are no reports on pole or leg kinetics before and after the intervention. Furthermore, none of the articles reviewed here attempted to determine how long the changes that occurred in response to the intervention persisted.

We speculate that increases in strength may not immediately influence the complex performance of XCS. Instead, several weeks or months of intervention and/or training after the intervention may be required to achieve more dynamic, explosive and higher production of skiing force and, thereby, improve technique. For example, it was recently shown that not only the level of strength *per se*, but also the timing of forces exerts considerable influence on the speed and economy of movements associated with any given skiing technique (Björklund et al., 2015; Stöggl et al., 2013; Stöggl and Holmberg, 2011; Stöggl and Holmberg, 2016). In addition, improvement of sprinting performance does not necessarily occur immediately after a period of resistance training (Moir et al., 2007). Combining general strength training with concomitant or subsequent training of complex technical skiing movements might augment the benefits of increased strength. In this connection, modern wearable technology and feedback systems (which can provide, e.g., simultaneous information concerning pole and leg forces) could help skiers alter their skiing technique, becoming more modern and dynamic, with well-coordinated application of force. However, these possibilities need to be explored rigorously.

In summary, the specific effects of strength training on XCS performance remain unclear. However, in no case has such training been reported to result in poorer performance and the question as to whether eliminating strength training by XC skiers would have any negative effects remains unanswered. This is directly related to the question concerning what the major goals of strength training should be, especially in light of the fact that by far most of the skier's time and effort is devoted to endurance training. Is strength training mainly functional and preventive or does it actually enhance performance? None of the studies included here evaluated prevention of injury, although, for example, in connection with team sports, increased strength is associated with less risk for injury (Gabbett, 2020; Malone et al., 2019). Moreover, improvement and/or maintenance of strength might also enhance the long-term performance of an athlete who trains and competes extensively, since such maintenance is an import aspect of sustainable athletic development.

Since none of the studies analyzed here involved strength training during the period of competition, the question also arises as to whether strength may be lost during these important months? It has been proposed, although on somewhat unclear grounds, that a single session of strength training per week would be sufficient to preserve strength during this period (Sandbakk, 2018). In the case of cycling the positive effects on strength and cycling performance observed following a period of strength training decline rapidly (e.g., within 8 weeks) after termination of this training (Ronnestad et al., 2016); whereas continued inclusion of one session of strength training each week further improved strength and cycling performance (Ronnestad et al., 2010). Furthermore, integration of speed endurance training (3 sets of 3 x 30-s sprints) into the regular program once a week during the transition period from preparation to competition improved sprint and maintained cycling performance (Almquist et al., 2020). It remains to be seen whether analogous investigations on XCS will result in similar outcomes. In this connection potential differences between, e.g., different regimens of strength training, men and women, sprint and distance skiers, and upper- versus lower-body muscles must be considered.

Limitations of the studies examined here

In general, the quality of the studies reviewed here was poor-to-fair (PEDro scores of 3 - 7), being good in only two cases. The methodological limitations include the relatively few participants (15 - 58), which reduces statistical power; the lack of control groups in four studies (Borve et al., 2017; Carlsson et al., 2017; Sagiev et al., 2020; Therell et al., 2021), with only men or no statistical comparison of the sexes (9 studies); and the lack of randomized controlled trials in eight studies. As mentioned above, all of the interventions may have been too short to result in pronounced muscle hypertrophy. In this context, strength training with more complex technique (e.g., training with free weights including Olympic lifts) requires appropriate time to develop proper lifting techniques and adequate load progression to guarantee safe application of higher loads. Furthermore, only a single study involved young XC skiers, and it is unclear when and how a young skier should begin to train strength in the same manner as an elite skier.

With respect to statistical analysis of the findings, the definition of statistical significance, effect sizes and confidence levels varied and, in some cases, ES could not be calculated on the basis of the data presented.

The total volume of endurance training varied considerably (4.8 - 15.3 h in 3 - 9 sessions per week (Losnegard et al., 2011; Nesser et al., 2004)), as did the level of detail provided concerning the weekly volume and intensity of training. The overall volume of endurance training involved in the interventions appears to be quite low in comparison to the amount of such training performed by world-class XC skiers (Holmberg, 2015; Sandbakk and Holmberg, 2017). Importantly, all of the studies that involved additional strength training stated that the amount of endurance training was the same for all participants and both groups. In no case was nutrition taken into consideration or muscles characterized utilizing, e.g., biopsies, EMG or ultrasound.

Only one article described testing of XCS performance on-snow, with most testing performance on ergometers or employing DP while standing and a few roller skis. Furthermore, in seven cases only the DP sub-technique, which does not adequately encompass the complexity of XCS, was tested. In addition, the relationship between the tests employed and actual XCS performance was often not reported and, in some cases can be questioned. This is particularly true concerning time-to-exhaustion tests, which are often criticized with respect to their reliability and validity (Currell and Jeukendrup, 2008).

Conclusions

Here, we present an up-to-date review of the effects of strength training on the strength and power, body composition, physiological and biomechanical characteristics, and performance of XC skiers. Available evidence indicates that XC skiers are stronger than many other endurance athletes and have become even stronger in recent decades. Most of the investigations reviewed here found moderate (ES = 0.56) positive effects of strength training on XCS performance. In general, strength training (2 - 3 times/week) focusing on high loads (hypertrophy and/or intramuscular coordination oriented), explosive strength and/or specific sprint interval or speed endurance training (intervals ≤20 s) is recommended for inclusion in XCS training. Future investigations should involve more prolonged interventions (e.g., covering an entire training year with its various phases, including strength maintenance training during the competition period); include both men and women, as well as upper- and lower-body muscles (trained separately and together); analyze muscle and blood parameters in individual participants; employ free weights and core training; and place special emphasize on the transfer of increased strength to improvement of biomechanical determinants of XCS performance.

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Key points

- Although available evidence indicates that XC skiers are stronger than many other endurance athletes and have become even stronger in recent decades, most of the investigations reviewed here found only moderate positive effects of strength training on XCS performance.
- The great variety of strength training described here has generally led to improvements in strength (e.g., 1RM), with inconsistent positive effects with respect to work economy/efficiency, $VO_{2max/peak}$, jump performance and body composition.
- Strength training (2 - 3 times/week) focusing on high loads (oriented towards intramuscular coordination and/or hypertrophy), explosive strength (power) and/or specific sprint endurance training are recommended for inclusion in XCS training, with special consideration of the individual athlete´s needs.
- The methodological quality of the articles examined was poor-to-fair, being good in only two cases. Future investigations should involve more prolonged interventions (including also the competition phase and long-term follow-up); include both men and women, as well as upper-, core and lower-body muscles; and place special emphasize on the transfer of increased strength to changes in the biomechanics and, consequently, on the performance of XCS.
- Although free weight training is a promising concept, studies of the effects of such training on XCS are sparse. If free weight training (e.g., Olympic lifts) which is technically complex, is included in the training regimen, early development of proper lifting technique, with special guidance and gradual increases in load, are recommended.

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