**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) |
|---|---|---|---|---|---|---|---|---|---|
| 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<br><br>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]<br><br>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]<br><br>Post-test TTEdiff was significantly reduced compared to C (-0.45 min vs. -1.32 min)<br><br>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.<br><br>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

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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)

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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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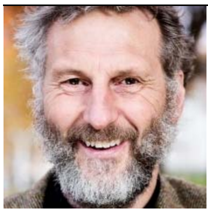

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## Key points

- 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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