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Sex Differences in Physiological Determinants of Performance in Elite Adolescent, Junior, and Senior Cross-Country Skiers

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Purpose: To compare sex differences in physiological determinants of skiing performance in elite adolescent, junior, and senior cross-country skiers matched for within-age-group performance level. ***Methods:*** Eight male and 12 female adolescent (15 [1] y), 8 male and 7 female junior (18 [1] y), and 7 male and 6 female senior (28 [5] y) skiers participated. Gross efficiency was calculated during submaximal uphill treadmill roller skiing (approximately 84% of peak oxygen uptake [$\dot{V}O_2$peak]) using the G2 ski-skating technique. Distance covered, $\dot{V}O_2$peak, and maximal accumulated oxygen deficit were established from a 3-minute time-trial. Fifteen-second maximal skiing power was calculated from an incremental treadmill speed test. Finally, upper- and lower-body maximal strength tests were conducted. ***Results:*** The 3-minute time-trial distance and maximal skiing power were, respectively, 23% and 15% (adolescent), 24% and 19% (junior), and 17% and 14% (senior) greater for men than women (all groups, $P \leq .01$, effect size [ES] = 2.43–4.18; very large). $\dot{V}O_2$peak relative to body mass was 17% (adolescent, $P = .002$, ES = 1.66, large), 21% (junior, $P < .01$, ES = 2.60, very large), and 19% (senior, $P < .01$, ES = 2.35, very large) greater for men than women. The within-age-group sex differences in gross efficiency, relative accumulated oxygen deficit, and strength were not significant, with the exception of greater lower-body strength in male than female juniors ($P = .01$, ES = 1.26, large). ***Conclusion:*** The within-age-group sex difference in skiing performance is of similar magnitude for adolescent, junior, and senior skiers. This difference can likely be attributed to the large to very large sex difference in $\dot{V}O_2$peak within all age-groups.

Keywords: maximal oxygen uptake, gross efficiency, anaerobic capacity, cross-country skiing, strength

The physical advantage of male compared with female athletes emerges during early adolescence, coinciding with the onset of male puberty (at approximately 12–13 y of age).[1] This is driven by sex-specific changes in circulating levels of hormones, which in turn result in greater muscle mass, lower relative body fat, and higher concentration of red blood cells and total red blood cell mass in men than in women.[2] Throughout adolescence, the sex difference in endurance performance approaches the sex difference observed in senior athletes,[3,4] which has been found to be approximately 8% to 12%.[2]

In cross-country (XC) skiing, male athletes typically perform 10% to 12% better compared with their female counterparts[2,5] depending on the subtechnique employed, as the sex difference is magnified when the contribution from poling increases.[6] Olympic XC skiing lasts from approximately 3 minutes to 2 hours in undulating terrain with varying speeds and which results in highly variable exercise intensities and complex interactions between energy system contributions.[7] Moreover, XC skiers frequently alternate between different subtechniques with different requirements for upper- and lower-body propulsion. Therefore, the development of endurance and upper- and lower-body power is critical for successful skiers.[8,9]

Maximal oxygen uptake,[10–12] the ability to efficiently transform metabolic energy into speed (eg, gross efficiency [GE])[10,13] and the ability to repeatedly perform, and recover from efforts above the maximal aerobic power[7] are key determinants for XC skiing performance. The increasing sex difference in maximal oxygen uptake relative to body weight during adolescence results in an increased sex difference in running performance among adolescent XC skiers (12–15 y).[14] Similar ski-specific results have also been observed in junior (approximately 17–18 y)[15] and senior (approximately 21–23 y)[5] skiers, and maximal oxygen uptake appears to be the primary determinant affecting the sex difference in XC skiing performance.[2,16,17] Similar skiing efficiency has been observed for senior male and female skiers,[17] and only one study has calculated the sex difference in anaerobic capacity, finding no difference relative to body mass in junior skiers.[15] However, limited research exists regarding the sex difference in adolescent athletes, and no previous studies have explored sex differences for these variables in XC skiers within different age-groups.

Differences in muscular strength may affect anaerobic capacity via greater muscle mass[18] and greater upper-body power in men compared with women may partially explain sex differences in XC skiing performance.[17,19] However, the importance of strength appears to be technique-dependent since the different subtechniques are characterized by varying contributions from upper- and lower-body propulsion,[6] as well as the individual athlete's ability to use their strength efficiently in the complex quadrupedal XC skiing techniques.[20,21] Furthermore, limited research exists on how the sex difference in strength affects skiing performance in adolescent and junior XC skiers.

Given the paucity of data relating to sex differences in adolescent XC skiers, our aim was to explore the sex difference in key physiological determinants of XC skiing performance within this age-group (approximately 14–15 y). Furthermore, we wanted to compare the sex difference in these elite adolescent skiers with the sex differences within elite junior (approximately 18 y) and elite senior skiers (approximately 28 y).

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Methods

Participants

Participant characteristics are summarized in Table 1. Participants and the parents of those participants under the age of 18 years were informed of the nature of the study and possible risks involved before giving their written consent. The study was approved by the Human Research Ethics Committee of the Norwegian School of Sport Sciences and registered with the Norwegian Center for Research Data.

Design

The present observational study explored submaximal (GE) and maximal (accumulated oxygen deficit [$\sum O_{2def}$], maximal aerobic power, and 15-s maximal power) treadmill roller ski performance using the ski skating subtechnique G2. In addition, maximal upper- and lower-body strength were tested. The adolescents were part of another study where the methods are described in detail.[22]

Procedures

Performance Level

Adolescent and Junior Skiers. Performance level was calculated as the percentage behind the mean time of the top 3 competitors during XC competitions for both adolescents and juniors (Table 1). For adolescents, performance level was calculated from the only national competition they have during the season ("Hovedlandsrennet," unofficial national championship). The skiers have the opportunity to compete in this race for 2 consecutive years (age 14–15 y) and, as such, performance level was calculated from the mean of these 2 races (5 skiers had only one race included in the calculation). The adolescent skiers were also part of another study testing 54 skiers and, in order to match this subgroup for performance level, we included all skiers who were less than 10% behind the mean time of the top 3 skiers in "Hovedlandsrennet."

For junior skiers, performance level was calculated from their 3 best distance races in the Norwegian national cup in the closest season to testing. The junior skiers were recruited from local XC skiing clubs and matched for performance based on previous results in the national XC skiing cup. Four of the junior skiers (2 male and 2 female) were part of the Norwegian junior national XC skiing team and had, in total, 4 medals from the FIS Junior World Ski Championships.

Senior Skiers. Performance level for the senior skiers was based on International Ski Federation (FIS) points at the time of testing[23] (Table 1). These athletes were at a world-class performance level and had won a total of 25 World Championship gold medals (men n = 3 and women n = 3), 7 Olympic gold medals (men n = 2 and

Table 1 Participant Characteristics in Performance Level, Anthropometrics, and Total Training Volume for Male and Female Skiers in the Different Age Groups

Age group and characteristic	Male (n = 8)	Female (n = 12)	*P*	ES
Adolescents				
Performance level, %[a]	9 (3)	7 (4)	.29	Small (0.50)
Age, y	15.0 (0.4)	14.7 (0.6)	.15	Small (0.56)
Body mass, kg	64.3 (5.9)	54.9 (6.1)	<.01	Large (1.56)
Body height, cm	177 (8)	165 (4)	<.01	Very Large (2.04)
Body mass index, kg·m^{-2}	20.5 (1.4)	20.3 (2.3)	.80	Trivial (0.10)
Total training, h·wk^{-1}	12.8 (3.4)	9.7 (2.6)	.04	Moderate (1.06)
	Male (n = 8)	**Female (n = 7)**	***P***	**ES**
Junior				
Performance level, %[a]	7 (7)	9 (7)	.67	Small (0.24)
Age, y	18 (1)	18 (1)	.87	Trivial (0.01)
Body mass, kg	69.7 (5.8)	61.1 (6.1)	.01	Large (1.45)
Body height, cm	181 (5)	168 (5)	<.01	Very Large (2.51)
Body mass index, kg·m^{-2}	21.3 (1.1)	21.7 (1.8)	.65	Small (0.27)
Total training, h·wk^{-1}	11.7 (2.0)	10.6 (1.2)	.28	Moderate (0.67)
	Male (n = 7)	**Female (n = 6)**	***P***	**ES**
Senior				
Performance level, FIS[a]	16 (15)	19 (18)	.69	Small (0.26)
Age, y	28 (5)	28 (3)	.99	Trivial (0.02)
Body mass, kg	73.8 (6.2)	63.4 (5.8)	.02	Moderate (0.97)
Body height, cm	178 (5)	170 (5)	<.01	Moderate (1.59)
Body mass index, kg·m^{-2}	23.3 (1.0)	21.8 (1.0)	.03	Moderate (1.40)
Total training, h·wk^{-1}	18.6 (1.7)	16.5 (1.9)	.77	Trivial (0.15)

Abbreviations: ES, effect size; FIS, International Ski Federation. Note: Data are displayed as mean (SD). *P* and ES represent the sex difference within age groups. The age of the adolescents was calculated from time of birth to the time of testing, while the age of juniors and seniors is shown in whole years. The total training volume is self-reported.
[a]See "Procedures" section for details regarding calculations of performance level for the different groups.

women n = 4) and had 115 individual world cup victories (men n = 5 and women n = 4), at the end of 2018/2019 season. One world-class biathlete who had performed at an international level in XC skiing was also included in this group.

Familiarization

Prior to the main testing, the adolescent skiers completed 2 sessions to familiarize them with the apparatus and the different test protocols. The juniors were already accustomed to using the roller skiing treadmill, and therefore only performed the second familiarization. The senior skiers had performed similar tests on numerous previous occasions and therefore performed only the main testing session due to time restrictions. The first familiarization consisted of 30 minutes submaximal roller ski skating, followed by 2 incremental speed tests (described below). The second familiarization session consisted of a 10-minute self-paced warm-up and two 5-minute submaximal G2 work bouts with cardiorespiratory measurements. The session ended with a familiarization to the strength testing protocol.

Three-Minute Maximal Time Trial

The adolescents and junior skiers performed the 3-minute maximal time trial (TT_{3min}) during the second familiarization, while the senior skiers performed the test after the incremental speed test during the main test session. TT_{3min} was a 3-minute maximal uphill time trial performed on the roller ski treadmill set to an 8° incline. The initial speed was 2.0 $m \cdot s^{-1}$ for the adolescent girls, 2.25 $m \cdot s^{-1}$ for the adolescent boys and junior women, 2.5 $m \cdot s^{-1}$ for the junior men and senior women, and 2.75 $m \cdot s^{-1}$ for the senior men. This speed was fixed during the first 30 seconds to prevent the skiers from going out too hard. Thereafter, the skiers themselves controlled the speed by adjusting their position on the treadmill relative to laser beams situated in front of and behind them. Each contact between the front or back wheels of the skis and the lasers induced a 0.25 $m \cdot s^{-1}$ increase or reduction in treadmill speed, respectively, conducted manually by the test leader. Visual feedback with respect to time was provided throughout. Cardiorespiratory variables ($\dot{V}O_2$ and respiratory exchange ratio) were monitored throughout the test and $\dot{V}O_2$peak was defined as the average of the 6 highest consecutive 5-seconds measurements (total 30 s). The $\sum O_{2def}$ was determined by subtracting the accumulated $\dot{V}O_2$ from the accumulated estimated total $\dot{V}O_2$ requirements during the $TT_{3min.}$[24] Performance was defined as the total distance covered.

Main Test Session

Submaximal Test. An overview of the main test session has been presented by Sollie et al (2021) in their Figure 2.[22] Following a 6-minute self-paced warm-up, participants completed 4 × 5-minute steady-state work bouts at a 6° incline. Only one 5-minute steady state bout was used in the present study for calculation of GE. The speed for this bout was calculated from the peak oxygen uptake ($\dot{V}O_2$peak) to target similar relative intensity between the male and female skiers in the adolescent groups (boys 83% [6%], girls 83% [4%] of $\dot{V}O_2$peak, $P = .81$) and junior groups (men 85% [6%], women 86% [7%], $P = .81$) while a rate of perceived exertion target (Borg scale 16) was used for the senior group (men 80% [4%], women 84% [4%], $P = .09$). The corresponding speed was 2.8 (0.2) and 2.3 (0.2) $m \cdot s^{-1}$ for the adolescents, 3.1 (0.2) and 2.5 (0.2) $m \cdot s^{-1}$ for the juniors, and 3.5 (0.1) and 3.0 (0.1) $m \cdot s^{-1}$ for the seniors, for males and females, respectively. GE was calculated as the propulsive power divided by the metabolic power.[24] Cardiorespiratory variables and HR were monitored from 2 to 5 minutes, and the average values used for further analysis. Rate of perceived exertion (Borg scale 6–20)[25] was recorded immediately upon cessation of exercise.

Incremental Speed Test. The test was performed 10 minutes after the submaximal test and was identical for all skiers. Testing started at an incline of 8° and a speed of 2.5 $m \cdot s^{-1}$ (estimated O_2-cost of approximately 66 $mL \cdot kg^{-1} \cdot min^{-1}$). The speed was increased by 0.25 $m \cdot s^{-1}$ every 15 seconds (estimated increase of approximately 7 $mL \cdot kg^{-1} \cdot min^{-1}$). Participants skied between 2 laser beams projected on to the treadmill in front of and behind them. When they were no longer able to keep the front wheels of the skis ahead of the rear laser beam for 2 consecutive G2 technique cycles, the test was ended. Propulsive power on the treadmill was calculated as the sum of power against gravity and power against rolling resistance, as previously described.[10] Maximal 15-second propulsive power (P_{max}) from the test relative to body mass was the performance outcome and was determined as

$$\begin{aligned}&\text{Work rate last step completed}\\&\quad+(\text{Increase in work rate each step}/\text{time each step})\\&\quad\quad\times\text{finished time final step.}\end{aligned}$$

Strength Tests. One-repetition-maximum strength tests were performed 20 minutes after the end of the roller ski tests with the same protocol as described by Losnegard et al.[26] The order of the tests was the same for all skiers. Strength was tested separately for each arm and leg to determine whether there was a difference in strength between the right and left side. All one-repetition maximum testing was supervised by the same investigator and conducted using the same equipment, with identical equipment setup for each skier.

The single-leg press was performed on an inclined (45°) leg press machine. Before the test, the correct depth (90° knee angle) was measured and noted. The test started with straight legs before the skiers lowered the weights to the correct depth whereby, they received a signal from the test leader to push back up. The attempt was considered valid when the weights were returned to the starting position.

For the single-arm pull-down, seating was adjusted to a 90° angle at the knees and hips, with a "neutral" spine and back resting against a backboard with both feet flat on the floor throughout the test. The "non-testing arm" rested on the opposite thigh. The pull was performed holding a custom-made ski pole grip positioned at the height of the forehead. The wire was parallel to the back support. Participants then pulled the grip straight down, with the pull defined as valid when the hand hit the bench, they were sitting on in one continuous motion, without bending the torso forward away from the backboard and with both feet kept on the ground.

Apparatus

The roller ski treadmill (Rodby) had dimensions of 3 × 4.5 m. To exclude possible variations in rolling resistance, all skiers used the same Swenor Skate roller skis (Sport Import AS) with wheel type 1 and a coefficient of friction of $\mu = 0.018$ and Rottefella binding systems (Rottefella AS) for all tests. The coefficient of friction was measured every week during the study period and was found to be consistent throughout. All participants used Swix Triac 1.0 and 3.0 poles of a self-selected length (approximately 90% of body height, Swix), modified with a tip specifically adapted for use on a roller skiing treadmill. Participants were secured to the treadmill by a safety harness connected to an emergency brake during testing. Height, body mass, and total mass including equipment were measured before each testing session (Seca model 877, Seca). $\dot{V}O_2$ was determined using a metabolic analyzer (Oxycon Pro, Jaeger GmbH), calibrated according to the manufacturer's instruction manual. Heart rate was measured throughout using a Polar M400 with a 1-Hz sampling rate (Polar Electro).

Statistical Analysis

Normality of the data was assessed using the Shapiro–Wilk analysis ($\alpha = .05$) and visual inspection of Q–Q plots. For statistical tests, a level of $P \leq .05$ was considered significant. Data are presented as mean (SD). Relative sex differences are presented as mean ± 95% confidence interval. Independent samples *t* tests were used to compare within-age-group sex differences and the overall sex difference (all age-groups combined) in TT_{3min} and P_{max}. A one-way analysis of variance was conducted to investigate the relative sex differences between age-groups. The magnitudes of the differences between variables were expressed as standardized mean differences (Cohen *d* effect size [ES]). The criteria to interpret the magnitude of the ES were as follows: trivial <0.2, small <0.6, moderate <1.2, large <2.0, and very large >2.0.[27] Statistical analyses were performed using GraphPad Prism (version 8, GraphPad Software) and SPSS statistical package (version 24). In calculations of percent sex differences, the female XC skiers were treated as the reference data (100%).

Results

Within-Age-Group Sex Differences in Performance

The distances covered during the TT_{3min} were 23%, 24%, and 17% longer in male than female skiers for adolescent, junior, and senior skiers, respectively, (all $P < .01$, all ES = very large [2.67–4.18], Figure 1A). When combining all age-groups, the distance covered was 24% longer for the male skiers compared with the female skiers ($P < .01$, ES = 1.86). Male skiers achieved 15%, 19%, and 14% higher P_{max} compared with their female counterparts in the adolescent, junior, and senior groups, respectively, (all $P < .01$, all ES = very large [2.43–2.67], Figure 1B). When combining all age-groups, the male skiers achieved 17% higher P_{max} compared with the female skiers ($P < .01$, ES = 2.0).

Within-Age-Group Sex Differences in Physiological Determinants

During the TT_{3min}, the male skiers achieved a 17% ($P < .01$, ES = 1.67), 21% ($P < .01$, ES = 2.59), and 19% ($P < .01$, ES 2.35) higher $\dot{V}O_2$peak compared with their female counterparts for adolescents, juniors, and seniors, respectively (Figure 1C). When combining all age-groups, the male skiers achieved 22% higher $\dot{V}O_2$peak compared with the female skiers ($P < .01$, ES = 1.92).

There were no significant sex differences in $\sum O_{2def}$ relative to body mass during the TT_{3min}. However, a moderate to large ES was found (Figure 1D, $P = .15$–$.27$ and ES = 0.73, 1.48, and 0.70, adolescent, juniors, and seniors, respectively). The relative $\sum O_{2def}$ accounted for 39% (8%) and 40% (15%) of the total energy contribution for the adolescents, 43% (7%) and 44% (9%) for the juniors, and 36% (5%) and 40% (6%) for seniors, for all men and women, respectively.

There were no differences in strength in any groups between the left and right arm or leg ($P > .05$ all groups). The strength values presented in this study are therefore the average of left and right sides combined. Both upper- and lower-body strength relative to body mass were similar between men and women in all age-groups, except lower-body strength was higher in male juniors compared with female junior skiers ($P = .01$, ES = 1.26; Figure 1E and 1F). Absolute strength (one-repetition maximum [in kilograms]) was, however, significantly greater for the male compared with the female skiers in all age-groups (adolescents; 25% [$P = .03$, ES = 1.25] and 31% [$P < .01$, ES = 1.96], juniors; 35% [$P < .01$, ES = 2.22] and 19% [$P = .02$, ES = 1.47], seniors; 46% [$P = .01$, ES = 2.09] and 30% [$P = .03$, ES = 1.65]) for lower- and upper-body strength, respectively.

There was no significant sex difference for GE within the different age-groups (P = all < .25, ES = adolescents; small [0.46], juniors; small [0.29], and senior; moderate [0.92]; Figure 1A) or rate of perceived exertion with 15 (1) for the adolescent group ($P = .91$, ES = 0.09), 14 (1) for the junior group ($P = .35$, ES = 0.51), and 14 (1) for the senior group ($P = .53$, ES = 0.40) during this submaximal work bout. Figure 1B shows the relationship between the metabolic power and propulsive power for the different age-groups during the submaximal work bout at similar relative intensities.

Between-Age-Groups Relative Sex Differences

The percentage sex differences within the age-groups for the different measures were not different between age-groups (TT_{3min}: $F_{2,20} = 2.09$, $P = .15$, P_{max}: $F_{2,19} = 1.36$, $P = .28$, VO_2peak: $F_{2,20} = .60$, $P = .56$, $\sum O_{2def}$: $F_{2,18} = .75$, $P = .49$, GE: $F_{2,19} = 2.16$, $P = .14$, pull-down: $F_{2,18} = 1.97$, $P = .17$, and leg press: $F_{2,16} = 1.75$, $P = .21$). Figure 3 presents an overview of this similar within age-group percentage sex difference between the age-groups for the performance tests, VO_2peak, $\sum O_{2def}$, GE, and strength.

Discussion

The present study demonstrates that the sex difference in performance in elite adolescent skiers (approximately 14–15 y) is of a similar magnitude as found in elite junior (approximately 18 y) and world-class senior XC skiers when matched for performance within age-groups. The within age-group sex differences in key physiological determinants of performance were also similar between the age-groups (Figure 3).

The sex difference in performance for sprint and distance World Cup races the last 20 years has been found to be approximately 9% to 12%,[28] similar to the 10% to 12% sex difference in performance observed in other endurance sports.[2] The sex difference of 14% to 24% in treadmill roller ski performance in the present study is greater but is in accordance with previous studies investigating laboratory performance in junior and senior skiers.[15,29] This is likely related to the fact that during competitions, approximately 25% of the time is spent in downhill sections where no propulsive power is required and the sex difference in speed thereby diminishes.[30] Furthermore, when skiing outdoors, the

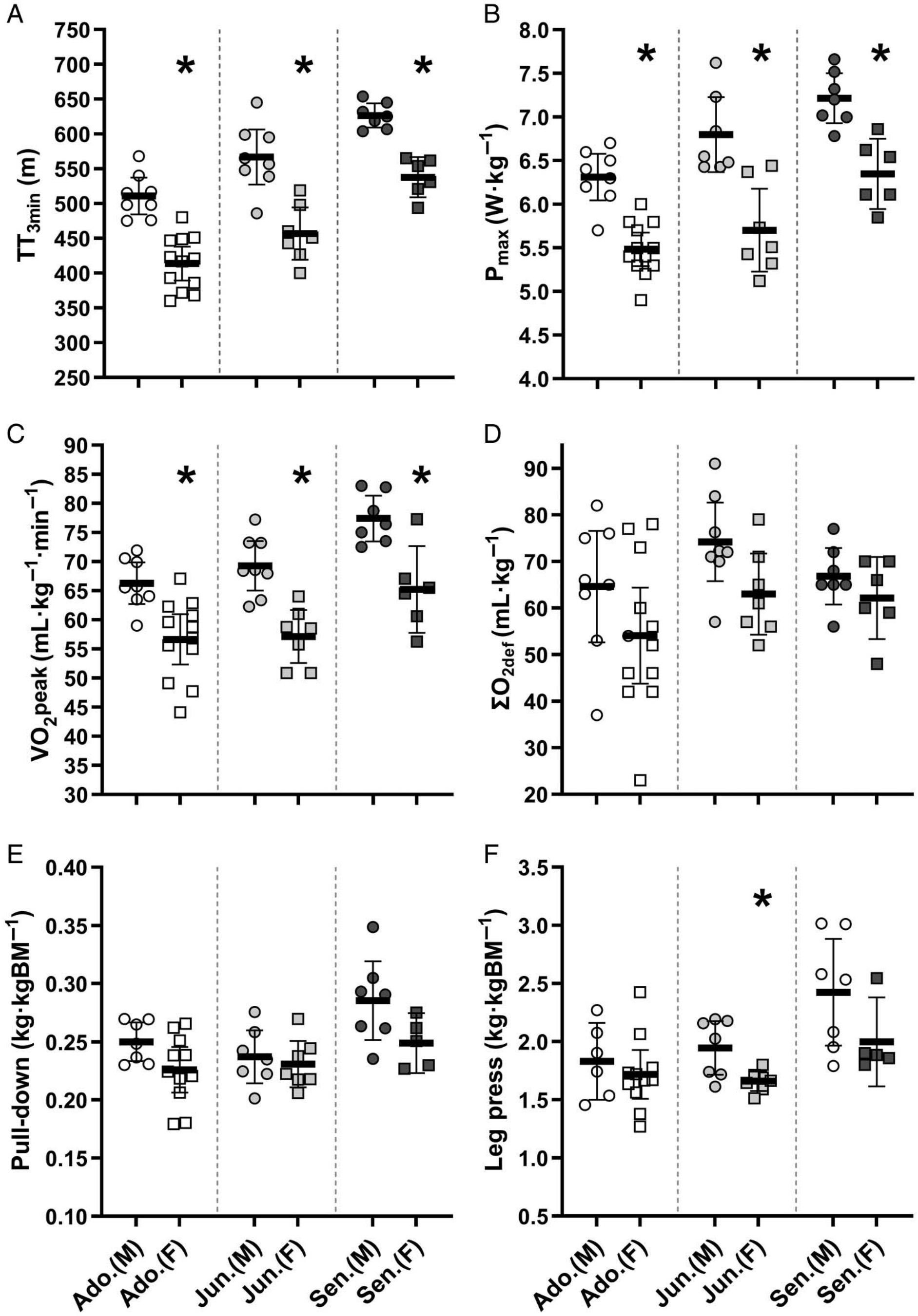

Figure 1 — Measurements from the maximal tests. (A) Distance covered (in meters) during the TT_{3min}; (B) P_{max}, highest 15-second power during the incremental speed test; (C) relative $\dot{V}O_2$peak; (D) relative $\sum O_{2def}$ from TT_{3min}; (E) single-arm pull-down; and (F) single-leg press with weight relative to body mass. Data are presented as mean ± 95% CI. Ado. indicates adolescent skiers; F, female; Jun., junior skiers; kgBM, kilograms body mass; M, male; P_{max}, propulsive power; Sen., senior skiers; TT_{3min}, 3-minute maximal time trial; $\dot{V}O_2$peak, peak oxygen uptake; $\sum O_{2def}$, accumulated oxygen deficit. *Significantly lower compared with male counterparts ($P < .05$).

higher speed of male compared with female athletes is accompanied by a quadratic increase in air resistance.[5,31]

In the present study, the overall sex difference (all age-groups combined) in performance for the TT_{3min} test (approximately 24%) was larger than the overall sex difference in performance for the P_{max} test (approximately 17%) ($P = .05$). The P_{max} test lasted approximately 1.3 minutes for the women when combining age-groups and approximately 2 minutes for the men. Consequently, the TT_{3min} test requires a relatively larger aerobic energy contribution compared with the P_{max} test (approximately 70%–75% vs approximately 55%–65%[32]) and thereby favors skiers with a higher maximal aerobic power. The greater sex difference in performance for the TT_{3min} than the P_{max} may therefore be related to the 22% higher $\dot{V}O_2$peak in men compared with women (age-groups combined). The sex difference in $\dot{V}O_2$peak as an important contributor to the sex difference in endurance performance is supported by previous findings in other endurance sports[2] and in elite senior skiers matched for

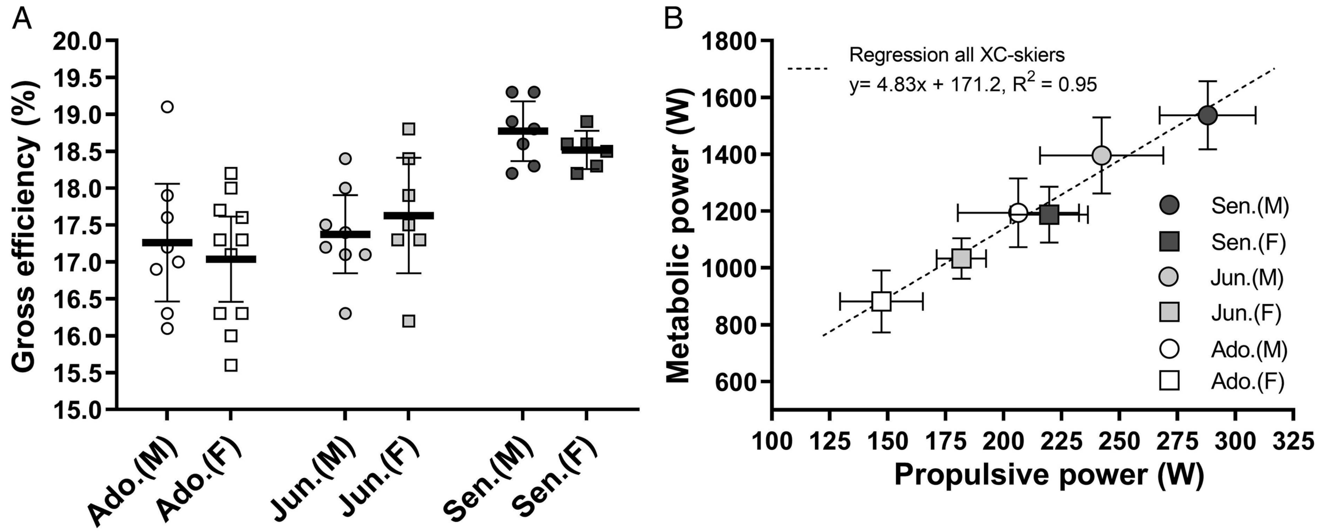

Figure 2 — Measurements from the submaximal work bout. (A) Gross efficiency (in percentage) for the different groups with individual data. Data are presented as mean ± 95% CI. (B) Submaximal metabolic power in relation to propulsive power. Data are presented as mean (SD). Ado. indicates adolescent skiers; F, female; Jun., junior skiers; Sen., senior skiers; M, male.

performance level.[29] The sex difference in $\dot{V}O_2$peak in the present study was somewhat higher than the 10% to 15% difference previously found in typical elite endurance athletes using lower-body propulsion,[16] but similar to endurance sports with combined upper- and lower-body propulsive power such as rowing.[33] The reason for this difference is currently not known. It has been suggested that a larger upper-body muscle mass[2] and a more effective utilization of upper-body strength in men compared with women can explain some of the differences.[6] However, the $\dot{V}O_2$peak in double poling relative to $\dot{V}O_2$peak in running (eg, mostly upper-body propulsive power vs lower-body propulsive power) does not seem to be different between sexes or performance levels.[28] It should be noted that few studies have included female skiers in such comparisons and this aspect should be further investigated in future research.

Previously, a similar metabolic demand relative to $\dot{V}O_2$max between elite male and female skiers has been found in outdoor race settings,[5] showing a similar relative anaerobic contribution to total energy requirements between sexes in XC skiing, as supported by the present study. Moreover, we did not find a sex difference in $\sum O_{2def}$ in any groups which is supported by the only previous study in XC skiing calculating sex differences in anaerobic capacity.[15] However, the moderate to large ES in the previous[15] and present study combined with a high typical error and coefficient of variation for the calculation of $\sum O_{2def}$[28] may indicate that a real difference was not detected (type 2 error).

Elite XC skiers are typically heavier than elite cyclists[34] and runners[35] indicating the need for well-developed upper- and lower-body power in XC skiing. The similar relative strength between sexes found in the present study is in contrast to a previous study of XC skiers.[19] However, the male skiers were stronger independent of body mass. This may affect the sex difference in outdoor XC skiing performance in flatter terrain since less work against gravity is required compared with uphill's, and total power is, therefore, more important than relative power.[36] Furthermore, the time window for the propulsion phase decreases with increasing speed and limits the possibility to generate force,[37] and the contribution from the upper body is an important performance characteristic for high-speed gears.[6] It has been proposed that increased strength in female skiers could increase performance,[25] but this has not been supported by a previous strength training intervention.[38] Moreover, early studies investigating the effect of strength training on skiing performance proposed that strength training enhanced the skiing efficiency and thus performance.[39,40] However, the relationship between increased strength and increased efficiency has later been questioned, and female skiers do not appear to have a greater positive effect of strength training than male skiers.[20,38] In addition, in the present study, we did not find a difference in skiing efficiency between sexes within any age-groups, corresponding to previous findings in senior skiers.[17] As such, we should use caution when trying to translate strength into a sport-specific performance,[25] and we suggest that the focus on strength training should be based on individual needs and not on sex.

Methodological Considerations

This study was part of a larger research project, with additional tests conducted during the main test session to those described here. Furthermore, breath by breath measures of $\dot{V}O_2$ were used for 4 male and 7 female adolescent skiers and 3 male and 2 female junior skiers, while averaged measures (mixing chamber) were used for the remaining adolescent, junior, and all senior skiers. This was due to a finding of approximately 9% underestimation of $\dot{V}O_2$ using breath by breath measures compared with mixing chamber measures in our lab during the research project.[41] However, since this study does not make comparisons between age-groups, this should not affect the conclusion. We present self-reported training volume in Table 1 to indicate approximate training volumes for each group. We did not collect detailed training data and therefore, these data are not included in the analyses. However, the male adolescents reported more weekly training compared with their female counterpart, which could possibly affect difference in performance and physiological determinants in this paper.

Practical Applications

Knowledge of what capacities are required for a specific sport is important for training optimization. The present study shows that

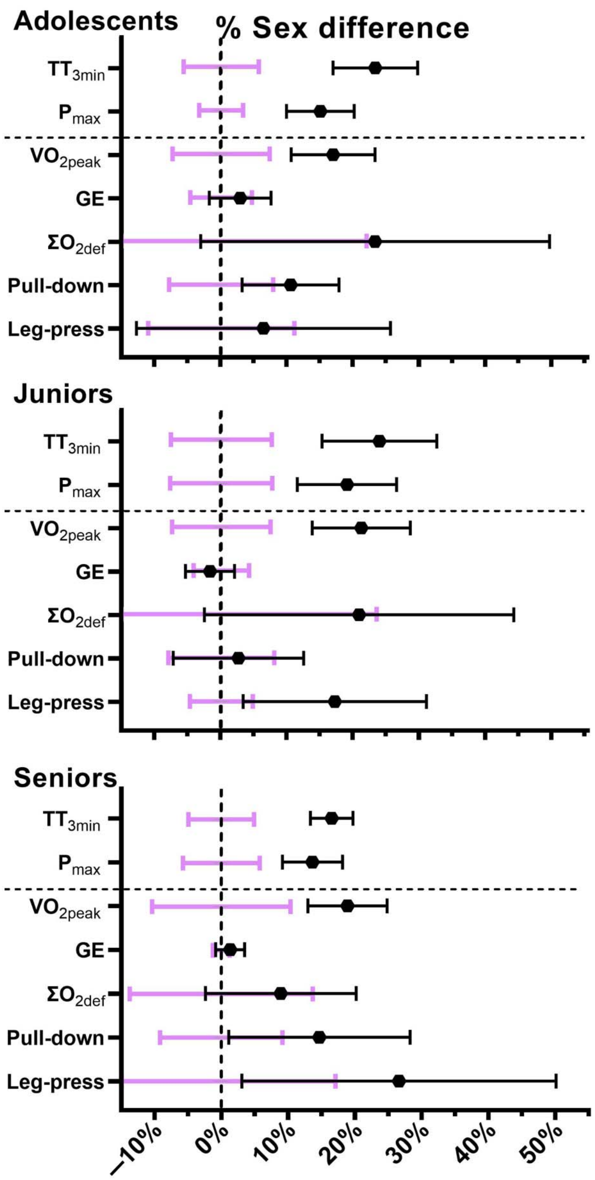

Figure 3 — Visualization of the percentage difference between male and female XC skiers for roller-ski performance, $\dot{V}O_2$peak, GE, $\sum O_{2def}$, pull-down, and leg-press strength in the different age-groups. The percentage sex differences within the age groups for the different measures were not different between age groups. The black symbols and black error bars represent mean ± 95% CI for the male skiers as percentages compared with the mean of the female skiers (defined as 100%) in the same age group (black dotted line at 0%). Purple (or gray, in black and white printed copy) error bars represent ±95% CI in percentages around the mean of the female skiers. Negative error bars below −15% are cut for visualization purposes. GE indicates gross efficiency; leg press, single-leg press; P_{max}, highest 15-second power output during the incremental speed test; pull-down, single-arm pull-down; TT_{3min}, 3-minute maximal time trial; $\dot{V}O_2$peak, peak oxygen uptake; $\sum O_{2def}$, accumulated oxygen deficit during the TT_{3min}.

when testing adolescent skiers (approximately 14–15 y) coaches and testing staff may expect similar sex differences in physiological determinants of performance as found in older skiers. Furthermore, our results demonstrate an overlap between sexes for individual values in the measured determinants where the best female skiers have higher values than the lowest ranked male skiers (Figures 1 and 2). This may imply that training to enhance these variables should not necessarily be differentiated based on sex, but rather that coaches should focus on tailoring training programs to target areas of most need.

Conclusion

Sex differences in XC skiing performance ranged from approximately 15% to 25% in lab-based performance tests within the different age-groups. These differences are already present in adolescent skiers (approximately 14–15 y) and remain consistent through junior age (approximately 18 y) and up to world-class senior performance level. The sex difference in performance can likely be attributed to the large to very large sex difference in $\dot{V}O_2$peak within all age-groups.

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