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1 **Peak age and relative performance progression in** 2 **international cross-country skiers**

3
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10
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15
16 This is an original investigation with 2 figures. The abstract consists of 248 and the text 3320
17 words.

18
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25 **Abstract**

26 **Purpose:** To quantify peak age and relative performance progression towards peak age in cross-
27 country (XC) skiing according to event type, sex and athlete performance level. **Methods:**
28 International Ski Federation (FIS) points (performance expressed relative to the best athlete) of
29 athletes born between 1981 and 1991 and competing in junior world championships or finishing
30 top 30 in world championships or Olympics were downloaded from the FIS website. Individual
31 performance trends were derived by fitting a quadratic curve to each athletes FIS point and age
32 data. **Results:** Peak age was 26.2 (2.3) years in distance and 26.0 (1.7) years in sprint events.
33 The sex difference in peak age in sprint events was ~0.8 years (small, $P = .001$), while there
34 was no significant sex difference in peak age in distance events ($P = .668$). Top-performers
35 displayed higher peak ages than other athletes in distance (mean difference, $\pm 95\%$ CL: 1.6 y,
36 ± 0.6 y, moderate, $P < .001$) and sprint events (1.0, ± 0.6 y, moderate, $P < .001$). FIS point
37 improvement over the 5 years preceding peak age did not differ between event types ($P = .325$)
38 while men improved more than women in both events (8.8, $\pm 5.4\%$, small, $P = .002$ and 7.5,
39 $\pm 6.4\%$, small, $P = .002$). Performance level had a large effect on improvement in FIS points in
40 both events ($P < .001$). **Conclusion:** This study provides novel insights on peak age and relative
41 performance progression among world-class XC skiers and can assist practitioners, sport
42 institutions and federations with goal setting and evaluating strategies for achieving success.

43
44 **Keywords:** age of peak performance, XC skiing, FIS points, elite athletes, gender differences
45

46 Introduction

47 Competitive performance in sports evolves and devolves throughout life via growth,
48 maturation, training and ageing. Understanding the relationship between age and performance
49 is important for practitioners, scientists, sport institutions and sport governing bodies, as such
50 knowledge is fundamental to goal setting, long-term training planning, season evaluation, talent
51 development benchmarking, athlete selection processes and allocation of funding and
52 resources.¹⁻³ Accordingly, several scientific publications are devoted to determination of age
53 of peak performance (peak age) and performance progression. So far, these analyses have been
54 mainly restricted to summer Olympic sports such as athletics,⁴⁻⁶ swimming⁷ and weightlifting.⁸

55 Cross-country (XC) skiing is a weight-bearing, full-body locomotion modality with
56 plyometric muscle actions involved, and this sport has always been a cornerstone of the winter
57 Olympic program. A variety of competition formats (sprint-, distance- and team-events) is
58 performed in the classic and skating styles, while managing hilly terrain.⁹ Individual races in
59 XC skiing range from sprint races, covering a distance of four times 1.3 to 1.8 km (initial
60 qualification and three knockout heats) to distance races, ranging from 10 to 30 km for women
61 and 15 to 50 km for men performed as either mass starts or individual time trials. Despite the
62 large number of published studies dealing with XC skiing, no valid information is currently
63 available regarding peak age and progression in relative performance in elite XC skiers.

64 A review of the literature within typical endurance sports showed that peak age and
65 performance progression differ as a function of sport events, athlete performance level and
66 sex.^{6,8,10} For example, peak age tended to increase with increasing event duration for endurance
67 events,¹⁰ although these trends were less pronounced in a recent study in athletics.⁶ Here, only
68 trivial to small differences were observed for the running disciplines between 800 and
69 10 000 m, but peak age was clearly higher in marathon compared to 1500 m. The race duration
70 in these events is comparable to a 50 km and sprint races, which raises the question about
71 possible differences in peak age between sprint and distance XC skiing. Similarly, athletes with
72 top 16 positions or better in international competitions tend to have ~1 y lower peak age across
73 several sports.^{6,8,11} Differences between male and female athletes, however, are varying among
74 endurance sports. While female long-distance runners displayed a 1-2 y higher peak age than
75 males,^{4,6} the opposite pattern was shown for triathletes¹¹ and swimmers.⁷ In contrast, women
76 showed a larger performance progression in the years leading up to peak age than men,⁶⁻⁸ which
77 was also the case for top-performers compared to athletes of lower level within both
78 sexes.^{6,8,11} Despite being a traditional Olympic sport,¹² cross-country skiing has continuously
79 evolved over the last decades, which subsequently could have influenced peak age.

80 In the context of talent selection and the development process, understanding the
81 relationship between junior and senior performance is of high interest, especially for sport
82 institutions. However, previous studies investigating athletics indicate that performing well at
83 junior age not necessarily leads to high senior performance.^{2,13}

84 The International Ski Federation (FIS) has recorded and systemized competition results
85 of international junior and senior athletes in XC skiing events over several decades. The
86 database is based on the FIS point system (see a detailed description in the methods), which
87 measures performance in relation to the best athletes (relative performance) and provides the
88 opportunity to investigate the long-term relative performance development of XC skiers.
89 Therefore, the aim of this study was to quantify peak age and progression in relative
90 performance in the preceding years to peak age in XC skiers according to event type, sex, and
91 athlete performance level. In addition, average absolute FIS points and a prediction of peak
92 performance based on junior performance were reported to provide reference values for sports
93 practice. Such information is useful for athletes, coaches and sport institutions for proper
94 goalsetting, talent developing benchmarking and evaluating strategies for achieving success.

95 **Methods**

96 *Data acquisition*

97 All data were collected from the FIS website (<https://www.fis-ski.com/en/cross-country>). FIS
98 has established the FIS point system, where an individual FIS race point is calculated for each
99 athlete competing in that specific race. The FIS race point takes race duration, the gap to the
100 winning athlete and the race format into account, by presenting race performances relatively.
101 In addition to the FIS race points, a FIS points list is provided. Here, athletes are ranked
102 according to the mean of their five best FIS race points during the last 365 days. Based on the
103 FIS point system, relative race performance and performance level can be monitored, even
104 though race distances, styles, profiles and weather conditions differ between races within the
105 same format. The FIS point system is the most valid way to express race performance and is
106 well established in science within the field of XC skiing.¹⁴⁻¹⁷ FIS race points of all athletes born
107 from 1981 to 1991 and competing in the junior world championships between 2001 and 2011
108 were selected, as long as these athletes were competing in FIS races (i.e. minimum three races
109 per year) for at least four years after they turned senior. To prevent us from missing late-
110 developing athletes, all top 30 finishers in Olympic winter games and world championships
111 were included, even when they did not compete in junior world championships but met the
112 other criteria. FIS points were calculated for each individual race and competitor according to
113 international competition rules with the following equation:

$$114 \quad \text{FIS race point} = \frac{F * T_x}{T_o} - F$$

115 where F is the factor for the race type (800 for interval starts, 1200 for sprints/pursuits with a
116 break, 1400 for mass starts and pursuits without a break), T_x and T_o are the competitor's and
117 winner's race time in seconds. Based on this calculation, the best race point value and thereby
118 the highest performance achievable is zero. To consider the participants' performance level for
119 all races other than world cup, world championships and Olympics, a race penalty was added
120 to each individual race point. The penalty was calculated by selecting the values of the top 5
121 finishers from the FIS point list and summing the three lowest values among them and
122 dividing the sum with 3.75. If this calculated race penalty was lower than the minimum penalty,
123 which is defined for each race category in the international competition rules, this minimum
124 penalty was applied. For all athletes included in this study, the three official races with the best
125 FIS race points of each season beginning from the last junior season until the end of the 2019
126 season or the individual end of the career were averaged separately for sprint and distance
127 events. When an athlete was not competing or was out of competition for more than two years
128 or having less than three sprint or three distance races per season after turning senior, data were
129 not included. To avoid the uncertainty of extrapolating performance trends, only athletes that
130 were active for at least five years prior to their estimated peak age were included. Athletes that
131 met the inclusion criteria for both event groups were additionally defined as all-round athletes
132 for complementary differentiation.

133 Additional data, such as sex, nationality and date of birth were also collected from the
134 FIS website. Results of all individual races at the Olympic winter games, world championships
135 and world cup of included athletes were used to categorize them as "top-performers" (having
136 finished top 3 at least twice in the named races which closely matches the criteria used in
137 previous studies^{8,11}) and "others". Age was calculated according to FIS international
138 competition rules by subtracting the year of birth from the year in which the season ended. As
139 all data collected are publicly available, individual informed consent was not required.

140 *Statistical Analysis*

141 A quadratic regression was performed to each athlete's performance and age data using SPSS
142 Statistics version 25 (IBM Corp., Armonk, NY, USA). Peak age was determined as the
143 minimum of the quadratic equation: Performance = $a \cdot \text{Age}^2 + b \cdot \text{Age} + c$. If the peak occurred
144 outside the age range of the performances or the quadratic curve was turned upside down, data
145 were not included. Relative performance progression preceding peak age was determined based
146 on the individual quadratic curve by subtracting peak performance from performance five years
147 prior to the estimated peak. Peak age and relative performance progression are presented as
148 mean and standard deviation (SD). The data were analyzed using mixed models with the
149 dependent variables peak age and relative performance progression, respectively, and the level
150 of significance was set at $\alpha \leq 0.05$. Event type (sprint or distance), sex and performance level
151 were each fixed explanatory variables for the three separate analyses. To respect the
152 hierarchical structure of the data, nationality was defined as a random factor. Chi square
153 statistics and -2 log-likelihood were used to check if a factor improved the fit of the model.
154 Effects sizes (ES) were calculated as Cohen's d, and criteria for interpretation were 0.0–0.2
155 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, and > 2.0 very large.¹⁸

156 **Results**

157 Overall, 9719 annual performances from 949 athletes were initially selected according to the
158 inclusion criteria. Due to inadequate data, 382 athletes had to be removed. Thus, 379 athletes
159 were finally included in the distance and 188 in the sprint group. The number of men was more
160 than 1.5-times the number of women (348 vs. 219) whereas there were almost 5-times less top-
161 performers (99) than other athletes (468). Mean goodness of fit of the individual quadratic
162 curves was similar in distance and sprint skiers ($R^2 = 0.73$ [0.22] and 0.73 [0.20]).

163 *Peak age*

164 Peak age was 26.2 (2.3) years in distance events and 26.0 (1.7) years in sprint events (ES 0.1,
165 $P = .003$). When analyzing all-round athletes only (frequently competing in both events), peak
166 age remained consistent. Trends of peak age in distance and sprint skiing across years of birth
167 are presented in Figure 1.

168 Figure 1

169 Differences in peak age as a function of sex and performance level were analyzed separately
170 by event type (Figure 2). Peak age did not differ between men and women in distance events
171 (mean difference, $\pm 95\%$ CL: <0.1 , ± 0.5 y, ES <0.1 , $P = .668$), whereas significant differences
172 were observed in sprint events (0.8 , ± 0.5 y, ES=0.5, $P = .001$). Top-performers in distance
173 events reached their peak age 1.6 y later than other athletes (± 0.6 y, ES=0.7, $P < .001$), while
174 top-performers in sprint events were 1.0 y older when reaching their peak age compared to
175 others (± 0.6 y, ES=0.6, $P < .001$).

176 Figure 2

181 *Relative performance progression*

182 No significant difference was found in percentage improvement in relative performance over
183 the five preceding years to peak age when comparing athletes in distance and sprint events
184 (48.3% [26.4%] and 52.4% [22.0 %], ES=0.2, $P = .325$).

185 Percentage improvements in relative performance over the five preceding years to peak
186 age according to sex and performance level are presented in Figure 3. Men improved more than
187 women in both distance (8.8, ± 5.4 %, ES=0.4, $P = .002$) and sprint events (7.5, ± 6.4 %, ES=0.4,
188 $P = .002$). Top-performers improved their relative performance more than others in both
189 distance (42.9, ± 6.1 %, ES=1.6, $P < .001$) and sprint events (26.9, ± 6.6 %, ES=1.4, $P < .001$).

190
191 Figure 3
192

193 *Relative performance at junior and peak age*

194 Relative performance based on individual quadratic trends in the last junior season (age 20 y)
195 was higher in distance events (87.9 [31.1] FIS points) than in sprint events (110.8 [25.6] FIS
196 points, ES=0.6, $P < 0.001$). Estimated relative peak performance was 43.3 (26.7) FIS points in
197 distance and 49.6 (34.9) FIS points in sprint events (ES=0.2, $P < .001$). No sex differences were
198 observed at peak or junior age in sprint events. In distance events men displayed better FIS
199 point scores than women at both junior (81.3 [27.7] and 99.1 [33.4] FIS points, ES=0.6
200 $P < .001$) and peak age (38.1 [26.3] and 52.1 [25.0] FIS points, ES=0.5, $P < .001$). Top-
201 performers in both event groups displayed better FIS point scores at junior age (58.2 [20.7] vs.
202 93.2 [29.7] FIS points in distance and 74.4 [25.0] versus 121.3 [42.1] FIS points in sprint
203 events, ES 1.4 and $P < .001$ in both events).

204 Relative performance at junior age based on the individual performance trends
205 explained 45 % of the variance in observed relative peak performance in distance ($R^2=0.445$,
206 $p < 0.001$) and 54 % in sprint events ($R^2 = .538$, $P < .001$).

207 The FIS point change scores were calculated based on original FIS point values for each
208 year, beginning from age 18 until 30 y, separated after event type, sex and performance level,
209 and can be found in the Supplementary Material (available online).

210 **Discussion**

211 This is the first study to quantify peak age and relative performance progression in distance and
212 sprint XC skiing. The main findings were firstly, that differences in peak age between distance
213 and sprint events were trivial, also when considering only all-round athletes that frequently
214 competed in both events. Relative performance among the analyzed athletes was higher in
215 distance events at any time compared to sprint events. Secondly, we found substantial sex
216 differences in sprint peak age, where men peaked ~ 0.8 y earlier than women. Male XC skiers
217 showed a higher relative performance progression in the five years preceding peak age. Lastly,
218 top-performers displayed a higher peak age, performed better at junior age and improved their
219 relative performance more in the preceding years to peak age than other athletes, independent
220 of event type.

221 The estimated peak ages of ~ 26 y in distance and sprint events are in line with previous
222 studies of athletics.^{4,6,10} It has to be mentioned that in all these sports, peak age might be affected
223 by training age, as for example an earlier specialization may increase the likelihood of an earlier
224 peak age. Our data do not support the trend of an increasing peak age with increasing event
225 duration in endurance events, as reported by Allen & Hopkins.¹⁰ However, the character of
226 sprint races in XC skiing is different to events in other sports that last ~ 3 -4 minutes, as the race
227 consists of four runs within 4 hours. It seems reasonable that different attributes like the ability
228 to recover fast after a run are needed in XC skiing sprint events, and that those attributes are
229 related to the demands of distance events. The trivial difference in peak age between XC skiing
230 event types demonstrates that a simultaneous development in sprint and distance skiing is
231 generally possible. This is supported by previous publications showing a high similarity in

232 training and physiology of sprint and distance skiers.¹⁹ The analyzed peak ages of all-round
233 athletes were consistent with the overall analysis and showed no chronological preference in
234 the development of these athletes. Interestingly, we observed a decreasing trend in peak age for
235 years of birth in both distance and sprint events, indicating that athletes who were born later
236 reached their peak age earlier. We can only speculate about possible reasons, and future studies
237 should examine even younger age groups and additional parameters such as training age to
238 confirm or disconfirm these findings.

239 No sex differences were observed in peak age in distance events. However, while peak
240 age among women in sprint events was in line with distance events, men displayed significantly
241 lower peak age in sprint events. We can only speculate for possible reasons. One could be the
242 tendency of a higher degree of specialization towards sprint or distance events in men, which
243 could support a theory of a less simultaneous development compared to generally more all-
244 round orientated women. This was supported by the higher percentage of all-round athletes
245 among female athletes. Our findings related to sex differences in peak age in distance events
246 are somehow contradictory to the trends reported by Haugen et al.⁶ More studies should focus
247 on sex-related performance trends in the context of endurance sports.

248 Top-performers in this study reached their peak age significantly later in both distance
249 (1.6 y) and sprint events (1.0 y) compared to other athletes. These findings differ from earlier
250 investigations on endurance athletes,⁶ but we can only speculate about possible reasons for
251 these discrepancies. As described by Tucker and Collins,²⁰ less successful athletes may have a
252 lower genetic potential or they do not manage to realize their potential to the same degree as
253 top-performers. Both aspects may explain an earlier turning point in sport careers. Furthermore,
254 it is also reasonable to assume that the rate of dropout due to a lack in motivation before
255 exploiting their individual potential is higher among less successful athletes, thereby affecting
256 the general career duration. Interestingly, peak age in top-performers was clearly higher in
257 distance than in sprint events. Although this finding contrasts with the overall results of the
258 present study, it is in line with earlier reports indicating increasing peak ages with increasing
259 event duration.¹⁰

260 Calculated FIS points for skiers in distance events were 6.3 points lower at peak age and
261 22.9 points lower at junior age compared to sprint events. The difference reflects generally
262 higher competitiveness in distance events, especially at junior age. However, the percentage
263 improvement towards peak age did not differ between distance and sprint events. We
264 hypothesize that sprint events have been introduced later and have not evolved in the same way
265 as distance events. Further, the number of competitors and the frequency of races in the two
266 event types differ, reflecting the number of athletes that met all inclusion criteria for this study
267 (i.e., three races per season per event), that was twice as high in distance events. In major
268 championships, such as world championships and Olympics, three individual distance races are
269 part of the program, while only one sprint race takes place. Thus, media attention and the higher
270 number of successful athletes favor distance events, which probably affects goal setting and the
271 focus of young athletes. Similar issues may explain the higher relative performance progression
272 in male versus female athletes. Most practitioners would argue that a smaller number of female
273 competitors also causes less pressure on individual development, which could affect the
274 percentage improvement.

275 Progression in relative performance in the years preceding peak age was clearly higher
276 in top-performers, which has also been reported in other sports.⁶ The clearly higher performance
277 level at junior age (large effects in both distance and sprint events) might be an explanation, as
278 this is associated with a higher aerobic capacity that probably allows top-performers to train
279 more and respond better.²¹⁻²³ Further, better athletes usually get more access to and higher
280 quality in support staff, including trainer, physician, psychologist and technician. However,
281 regression analyses of relative junior and peak performance based on the individual
282 performance trends revealed R^2 values of only ~ 0.5 . Future studies should therefore aim to

283 investigate the longitudinal development in training and physiology with respect to different
284 performance levels to get a deeper understanding of the long-term development in endurance
285 sports.

286 There are several limitations to the study design. Firstly, time as direct measurement of
287 performance in a XC skiing race is not comparable with other races, due to varying race profiles,
288 weather and snow conditions. Hence, performance can only be described in relation to the
289 winner (FIS-points). Thus, all expressions of performance are influenced by the level of the
290 best performing athletes. Consequently, the percentage progression in relative performance
291 cannot be compared to previous data. Moreover, FIS-points in sprint are only related to the
292 qualification and not to overall sprint performance. However, additional analysis of 13068
293 individual results revealed a strong correlation ($r=0.660$, $p<0.001$) between the rankings in
294 qualification and final. Furthermore, no data is available regarding the participants training age,
295 which is probably a strong predictor of peak age. Finally, potential use of prohibited substances
296 (doping) and improvement in equipment may have influenced individual performance data.

297 **Practical applications**

298 This study provides novel insight on peak age and relative performance progression in world-
299 class XC skiing contestants that can be useful for goal setting, long-term training planning,
300 seasonal evaluations, talent development benchmarking, athlete selection processes and
301 allocation of funding and resources. Specifically, these findings indicate that practitioners, sport
302 institutions and federations aiming for fast success should focus specifically on sprint skiing
303 and female athletes and should not consider junior performance as primarily criterion for talent
304 selection. Furthermore, the identified dynamics in peak age are useful as motivational factor
305 for young athletes. In addition, our observations also provide a point of departure for future
306 studies aiming to investigate the possible underlying mechanisms related to peak age and
307 relative performance progression across athletes, exercise modalities and physiological
308 capacities.

309 **Conclusions**

310 The present study revealed that mean peak age was ~26 y in both distance and sprint skiing,
311 indicating that a simultaneous development in both events is possible. Male XC skiers showed
312 a higher relative performance progression in the five years preceding peak age. Top-performers
313 performed better at junior age, improved more and over a longer time frame than other athletes.
314 Moreover, we found that competitiveness was lower in sprint events and among women in both
315 event types. Furthermore, we found that junior performance can only account for half of the
316 variance in peak performance.

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319

320 **References**

- 321 1. Bongard V, McDermott AY, Dallal GE, Schaefer EJ. Effects of age and gender on
322 physical performance. *Age*. 2007;29(2-3):77-85. doi:10.1007/s11357-007-9034-z
- 323 2. Vaeyens R, Güllich A, Warr CR, Philippaerts R. Talent identification and promotion
324 programmes of olympic athletes. *J Sports Sci*. 2009;27(13):1367-1380. PubMed ID:
325 19787538 doi:10.1080/02640410903110974
- 326 3. Berthelot G, Len S, Hellard P, et al. Exponential growth combined with exponential
327 decline explains lifetime performance evolution in individual and human species. *Age*.
328 2012;34(4):1001-1009. doi:10.1007/s11357-011-9274-9
- 329 4. Hollings S, Hopkins W, Hume P. Age at peak performance of successful track & field
330 athletes. *Int J Sport Sci Coach*. 2014;9(4):651-661. doi:10.1260/1747-9541.9.4.651
- 331 5. Tønnessen E, Svendsen IS, Olsen IC, Guttormsen A, Haugen T. Performance
332 development in adolescent track and field athletes according to age, sex and sport
333 discipline. *PLoS One*. 2015;10(6):1-10. doi:10.1371/journal.pone.0129014
- 334 6. Haugen TA, Solberg PA, Foster C, Morán-Navarro R, Breitschädel F, Hopkins WG.
335 Peak age and performance progression in world-class track-and-field athletes. *Int J*
336 *Sports Physiol Perform*. 2018;13(9):1122-1129. PubMed ID: 29543080
337 doi:10.1123/ijssp.2017-0682
- 338 7. Allen SV, Vandenberg TJ, Hopkins WG. Career performance trajectories of
339 Olympic swimmers: Benchmarks for talent development. *Eur J Sport Sci*.
340 2014;14(7):643-651. PubMed ID: 24597644 doi:10.1080/17461391.2014.893020
- 341 8. Solberg PA, Hopkins WG, Paulsen G, Haugen TA. Peak Age and Performance
342 Progression in World-Class Weightlifting and Powerlifting Athletes. *Int J Sports Physiol*
343 *Perform*. 2019;14(10):1357–1363. doi:10.1123/ijssp.2019-0093
- 344 9. Sandbakk Ø, Holmberg H-C. Physiological Capacity and Training Routines of Elite
345 Cross-Country Skiers: Approaching the Upper Limits of Human Endurance. *Int J Sport*
346 *Physiol Perform*. 2017;12(8):1003-1011. doi:10.1123/ijssp.2015-0012
- 347 10. Allen S V., Hopkins WG. Age of Peak Competitive Performance of Elite Athletes: A
348 Systematic Review. *Sports Med*. 2015;45(10):1431-1441. doi:10.1007/s40279-015-
349 0354-3
- 350 11. Malcata RM, Hopkins WG, Pearson SN. Tracking career performance of successful
351 triathletes. *Med Sci Sports Exerc*. 2014;46(6):1227-1234. PubMed ID: 24576862
352 doi:10.1249/MSS.0000000000000221
- 353 12. Sandbakk O. The evolution of champion cross-country-skier training: From lumberjacks
354 to professional athletes. *Int J Sports Physiol Perform*. 2017;12(2):254-259. PubMed ID:
355 28095069 doi:10.1123/ijssp.2016-0816
- 356 13. Boccia G, Cardinale M, Brustio PR. Performance progression of elite jumpers: early
357 performances do not predict later success. *Scand J Med Sci Sport*. 2021;31:132-139.
358 doi:10.1111/sms.13819
- 359 14. Andersson E, Supej M, Sandbakk Ø, Sperlich B, Stöggl T, Holmberg HC. Analysis of
360 sprint cross-country skiing using a differential global navigation satellite system. *Eur J*
361 *Appl Physiol*. 2010;110(3):585-595. PubMed ID: 20571822 doi:10.1007/s00421-010-
362 1535-2
- 363 15. Sandbakk Ø, Ettema G, Holmberg HC. Gender differences in endurance performance by
364 elite cross-country skiers are influenced by the contribution from poling. *Scand J Med*
365 *Sci Sport*. 2014;24(1):28-33. doi:10.1111/j.1600-0838.2012.01482.x
- 366 16. Svendsen IS, Gleeson M, Haugen TA, Tønnessen E. Effect of an intense period of
367 competition on race performance and self-reported illness in elite cross-country skiers.
368 *Scand J Med Sci Sport*. 2015;25(6):846-853. doi:10.1111/sms.12452
- 369 17. Hébert-Loisier K, Zinner C, Platt S, Stöggl T, Holmberg HC. Factors that Influence the

- 370 Performance of Elite Sprint Cross-Country Skiers. *Sport Med.* 2017;47:319-342.
371 doi:10.1007/s40279-016-0573-2
- 372 18. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies
373 in sports medicine and exercise science. *Med Sci Sports Exerc.* 2009;41(1):3-13.
374 PubMed ID: 19092709 doi:10.1249/MSS.0b013e31818cb278
- 375 19. Sandbakk Ø, Holmberg HC. A reappraisal of success factors for olympic cross-country
376 skiing. *Int J Sports Physiol Perform.* 2014;9(1):117-121. PubMed ID: 24088346
377 doi:10.1123/IJSPP.2013-0373
- 378 20. Tucker R, Collins M. What makes champions? a review of the relative contribution of
379 genes and training to sporting success. *Br J Sports Med.* 2012;46(8):555-561. PubMed
380 ID: 22535537 doi:10.1136/bjsports-2011-090548
- 381 21. Losnegard T. Energy system contribution during competitive cross-country skiing. *Eur*
382 *J Appl Physiol.* 2019;119(8):1675-1690. PubMed ID: 31076890 doi:10.1007/s00421-
383 019-04158-x
- 384 22. Sandbakk Ø, Hegge AM, Losnegard T, Skattebo Ø, Tønnessen E, Holmberg HC. The
385 physiological capacity of the world's highest ranked female cross-country skiers. *Med*
386 *Sci Sports Exerc.* 2016;48(6):1091-1100. PubMed ID: 26741124
387 doi:10.1249/MSS.0000000000000862
- 388 23. Sandbakk Ø, Holmberg HC, Leirdal S, Ettema G. The physiology of world-class sprint
389 skiers. *Scand J Med Sci Sport.* 2011;21(6):9-16. doi:10.1111/j.1600-0838.2010.01117.x
390

391 **Figure captions**

392 **Figure 1.** Age of peak performance among cross-country skiers across years of birth in
393 comparison to the overall means (dotted lines). Data are means and standard deviations.

394
395 **Figure 2.** Age of peak performance among cross-country skiers across sex (Panel A) and
396 performance level (Panel B). Data are means and standard deviations. Effect sizes: * trivial, **
397 small, *** moderate.

398
399 **Figure 3.** Improvement in FIS points in cross-country skiers over the five preceding years to
400 age of peak performance across sex (Panel A) and performance level (Panel B). Data are means
401 and standard deviations. Effect sizes: ** small, **** large.

Figure 1

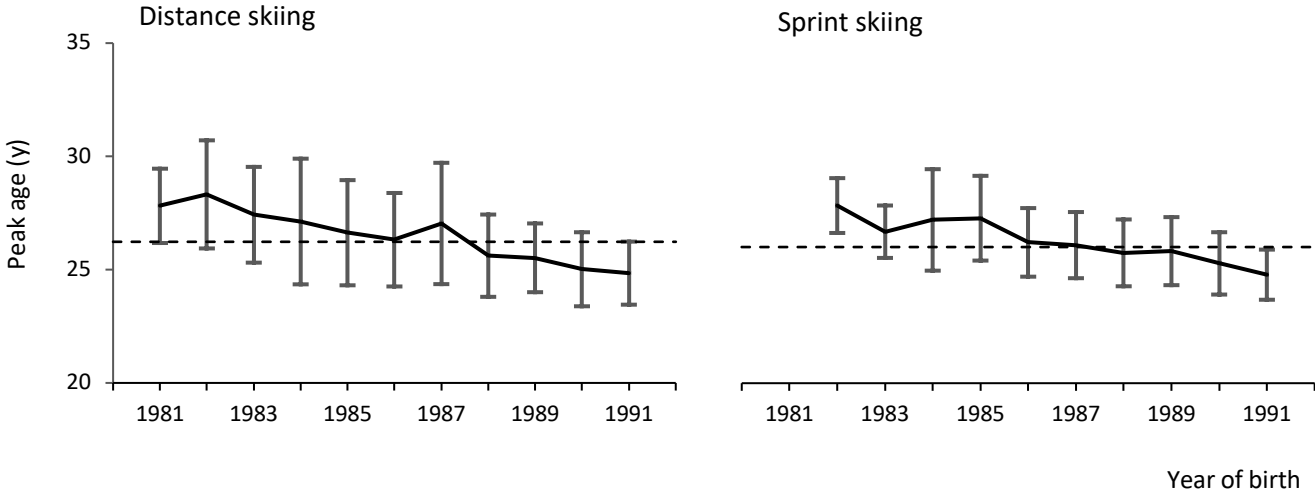


Figure 2

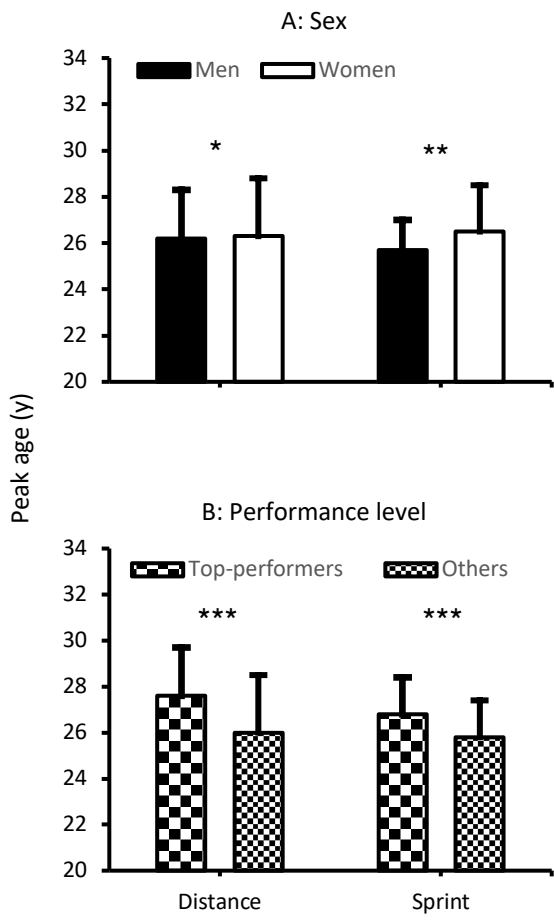


Figure 3

