Anthropometric, physiological and performance developments in cross-country skiers

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Abstract

Purpose: To describe changes in laboratory-assessed anthropometric and physiological characteristics, training volumes and competitive performance in national development-team cross-country (XC) skiers over a 25-month period, and to analyze whether changes in competitive performance could be predicted by changes in laboratory-assessed qualities and training volumes.

Methods: Data collected over 25 months from 30 national development-team XC skiers (14 women, 16 men; age 18–23 y) were analyzed retrospectively using multivariate statistics. Anthropometric and physiological characteristics were assessed via dual-energy X-ray absorptiometry and incremental roller-ski treadmill tests, respectively. Total training volumes and distributions of low- and high-intensity training (LIT and HIT) were analyzed from online training diaries, and competitive performance was determined by International Ski Federation (FIS) distance and sprint points.

Results: Whole- and upper-body lean mass increased in the full cohort of skiers (n=30; both $p<0.05$), while lower-body lean mass, whole-body fat mass, speed and oxygen uptake ($\dot{V}O_2$) at a blood lactate concentration (BLa) of 2 and 4 mmol·L^{-1}, as well as time-trial (TT) completion time, power output and peak $\dot{V}O_2$, improved in the women only (all $p<0.05$). Valid predictive models were identified for female skiers' best FIS distance points ($R^2=0.81$ / $Q^2=0.51$) and changes in FIS distance points ($R^2=0.83$ / $Q^2=0.54$), with body mass, fat mass, lean mass, $\dot{V}O_{2peak}$ and speed at a BLa of 4 mmol·L^{-1} identified as consistently important variables for projection.

Conclusion: The valid prediction of competitive performance was achieved for women only in distance events. This study suggests that improvements in body composition and aerobic capacity may be more beneficial for elite female development-level skiers than for their male counterparts. These results have implications for athlete selection and performance development.

Key Words

athlete testing; FIS points; longitudinal monitoring; multivariate statistics; Nordic; prediction

Introduction

Cross-country (XC) skiing is a demanding and complex endurance sport involving different techniques (classic and skate) and sub-techniques (i.e., “gears” within each technique), race times ranging from a few minutes to several hours and race courses that combine undulating, uphill, downhill and flat terrain. A substantial body of research has examined the physiological demands of XC skiing and the physical qualities that may be predictive of successful performance in male and female XC skiers at both junior and senior levels (1–3). Although the physiological determinants of XC skiing performance can be assessed using treadmill roller-ski tests in controlled laboratory environments (4–6), real-world competitive XC skiing performance is more complex. This is due to numerous uncontrollable factors such as weather and snow conditions, quality of ski equipment and waxing (i.e., ski grip and/or glide properties) (7), as well as race tactics and pacing (8). As such, International Ski Federation (FIS) points are often used as a representation of long-term performance in male and female XC skiers (9–11).

Correlational and multiple linear regression statistical approaches have previously been used to predict FIS points (i.e., competitive performance) in XC skiers from physical and physiological qualities assessed in laboratory environments (3,9,10,12–15). These analyses have identified numerous variables that correlate with FIS points, including lean body mass (10,12,13), the speed at a blood lactate concentration (BLa) of 4 $\mathrm{mmol \cdot L^{-1}}$ (3), gross efficiency (GE) (1,14,16), peak oxygen uptake ($\dot{V}O_{2peak}$) (3,12,13,17) and roller-ski time-trial (TT) performance (15). Furthermore, multiple linear regression analyses have identified that successful performance in XC skiing is likely influenced by a combination of these factors, rather than by any one factor in isolation (9,12,15,18). However, previous research and statistical texts have highlighted that the bivariate and multiple linear regression analyses commonly employed in sport science research may be insufficient to reveal complex interactions between variables, and how they influence a specific response (19,20). A more robust and informative procedure may be to employ multivariate statistical methods, which account for interactions between a broad spectrum of qualities, to identify valid predictive models of competitive performance (19).

Previous studies have typically related FIS points to laboratory test data collected on a single occasion, representing only a “snapshot” of XC skiers’ characteristics and capacities. Longitudinal changes in anthropometric and physiological qualities in junior skiers have been documented, providing useful information for athlete selection strategies (21–23). However, limited information is available relating to how changes in physical parameters in XC skiers may influence developments in competitive performance (17,24), and which metrics may be influential in the projection of long-term changes in performance. Furthermore, no previous research has examined how changes in physical parameters and training volumes influence performance development. Such studies are particularly important in cohorts of developmental-level athletes, who may experience greater changes in anthropometric and physiological qualities compared to more senior athletes.

The aim of the present study was to describe changes in laboratory-assessed anthropometric and physiological characteristics, training volumes and field-based competitive distance and sprint race performance in national development-team XC skiers over a longitudinal period. Furthermore, multivariate statistical methods were used to analyze whether changes in the laboratory-assessed qualities and training volumes were predictive of changes in competitive performance.

Methods

Design

Data collected from a national XC-ski development team over a 25-month period (March 2017 to April 2019) were analyzed retrospectively to examine whether changes in anthropometric and physiological characteristics assessed in a laboratory setting, as well as training volumes, were predictive of changes in competitive performance, defined as FIS distance and sprint points. Anthropometric characteristics included stature, body mass, body mass index (BMI), whole-body lean mass (LBM), upper-body lean mass, lower-body lean mass and whole-body fat mass. Submaximal physiological variables included $\dot{V}O_2$ (in $L \cdot min^{-1}$, $mL \cdot kg^{-1} \cdot min^{-1}$ and $mL \cdot kg\ LBM^{-1} \cdot min^{-1}$), GE, and speed, heart rate (HR) and $\dot{V}O_2$ at a BLa of 2 and 4 $mmol \cdot L^{-1}$. Maximal variables included TT completion time expressed in seconds, and average relative power output (PO, in $W \cdot kg^{-1}$), $\dot{V}O_{2peak}$ (in $L \cdot min^{-1}$, $mL \cdot kg^{-1} \cdot min^{-1}$ and $mL \cdot kg\ LBM^{-1} \cdot min^{-1}$) and peak BLa. Specific details relating to measurement of the aforementioned metrics are presented in the *"Body composition"* and "*Roller-ski exercise assessments*" sections, where appropriate.

Participants

Thirty national development-team XC skiers (14 women: age 20 ± 1 y, stature 1.69 ± 0.05 m, body mass 62.9 ± 5.1 kg; 16 men: age 21 ± 2 y, stature 1.81 ± 0.06 m, body mass 76.0 ± 7.1 kg) provided written informed consent to participate in this study. The criteria for inclusion required that skiers had performed laboratory testing on at least two occasions across different years within the 25-month period. All skiers were over 18 years of age at the time of testing. All participants were fully informed about the nature of the study before consenting for their data to be included. The study was preapproved by the regional ethical review board in Umeå, Sweden (reference: 2018-46-31M).

Data selected for analysis

Body composition assessments via dual-energy X-ray absorptiometry (DXA) and roller-ski exercise assessments were conducted at the Swedish Winter Sports Research Centre within two annual test periods, once between March and June and once between August and October. The 25-month observational period spanned March 2017 to April 2019, thereby encompassing five test periods. It was not possible to test all skiers on all five occasions due to illness, injury or lack of availability. In total, 90 DXA scans (41 in 2017, 25 in 2018 and 24 in 2019) and 108 roller-ski exercise assessments (47 in 2017, 31 in 2018 and 30 in 2019) were performed, equating to a mean of 3 ± < 1 DXA scans and 4 ± < 1 roller-ski assessments per skier (DXA scans: women 4 ± 1, men 2 ± < 1; roller-ski assessments: women 4 ± < 1, men 3 ± < 1). Anthropometric and physiological data selected for analyses for each individual skier were from the March–June test window, as these data were collected closest to the dates used for calculating the end-of-season FIS points, which was between the 22nd–28th of March each year (i.e., 2017, 2018 and 2019).

Calculation of FIS points

Briefly, a skier's FIS points score at any given time is calculated as the average of their top five results (in FIS points) over the last 365 days (an adjustment factor of > 1.0 is applied if fewer than five results are available) (25). The FIS points gained in a single competition are determined by adding the individual race points (P) to the race penalty score, where P is calculated as follows:

$$P = \frac{F \times Tx}{To} - F$$

F is the race factor (800 for all individual time trials; 1200 for sprints and pursuit races; 1400 for mass start and skiathlon races), *Tx* is the race time (in seconds) and *To* is the winning race time (in seconds). Hence, lower race points indicate a better performance. The race penalty score is calculated by summing the three highest FIS points scores (from the current FIS points list) from the top five finishers in the respective competition, then dividing by 3.75. Separate FIS points lists are used for sprint and distance competitions and these are publicly available at fis-ski.com. FIS distance and sprint points lists were retrieved for this study on 18th November 2019.

The FIS points from the end of the 2017 (i.e., 23rd March 2017), 2018 (i.e., 22nd March 2018) and 2019 (i.e., 28th March 2019) competitive seasons were used to ensure that data were representative of an entire season's competition performances. Over the observational period, 1561 races (women = 729, men = 832) were used in the FIS points calculations. This equated to a mean of 17 ± 5 races per skier (2017: women 15 ± 6, men 16 ± 4; 2018: women 16 ± 5, men 16 ± 4; 2019: women 21 ± 6, men 19 ± 4).

Body composition assessments

All body composition measures were conducted via DXA (Lunar iDXA, General Electric Company, Madison, WI, USA). Lean and fat mass were quantified *post hoc* using the iDXA software (Encore 2007, Version 11.4). Participants were instructed to wear underwear or light training clothing and to remove all items containing metal and/or piercings and lie still throughout the scan, which took ~ 7 min. All scans took place in the morning following an overnight fast. A more detailed description of the DXA procedures have been published previously (26).

Roller-ski exercise assessments

All roller-ski exercise assessments involved diagonal-stride roller skiing on a motorized treadmill (belt dimensions 3.3 x 2.5 m; Rodby Innovation AB, Vänge, Sweden). All skiers used

Pro-Ski C2 roller skis (Sterners, 120 Dala-Järna, Sweden) equipped with NNN (Rottefella, Klockarstua, Norway) or SNS (Salomon, Annecy, France) bindings with rolling resistances standardised at 0.0235 and 0.0240, respectively. Rolling resistances were determined using methods detailed by Ainegren et al. (27). Expired air was recorded as 10-s averages during roller-ski exercise using an AMIS 2001 metabolic system (model C, Innovision A/S, Odense, Denmark), which was calibrated before each testing session using a 3-L syringe (Hans Rudolph, Kansas City, Missouri, USA), ambient air and a calibration gas (Strandmöllen AB, Ljungby, Sweden) with known concentrations of 16% O_2 and 4.5% CO_2. HR was monitored continuously throughout the roller-ski exercise tests using a standard watch and chest strap (Polar S810, Polar Electro Oy, Kempele, Finland).

Skiers performed a 6-min warm up at the same workload as the first stage of the subsequent submaximal test. Following warm up, the incremental submaximal protocol consisted of 4–6 stages each lasting 4 min and separated by 1-min rest intervals. The women began the submaximal test at 8 $km \cdot h^{-1}$ and a gradient of 3° and the men commenced at 9 $km \cdot h^{-1}$ and 4°. Speed was increased by 0.5 $km \cdot h^{-1}$ and gradient by 1° per stage. Respiratory variables ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$ and RER) and HR were calculated as the mean over the last 30 s of each submaximal stage. The treadmill was stopped during each 1-min break for fingertip blood sampling to subsequently determine BLa (Biosen S-line, EKF Diagnostic GmbH, Magdeburg, Germany) and to record the rating of perceived exertion (RPE; Borg-scale 6–20). The submaximal test was terminated after the stage at which the RER exceeded 1.00, $\dot{V}E/\dot{V}O_2$ exceeded 30 and HR exceeded 90% of the maximal HR reported by the skiers. Speed, HR and $\dot{V}O_2$ corresponding to a BLa of 2 and 4 $mmol \cdot L^{-1}$ were calculated from the individual linear relationships between BLa, speed, HR and $\dot{V}O_2$ (28). $\dot{V}O_2$ (in $L \cdot min^{-1}$, $mL \cdot kg^{-1} \cdot min^{-1}$ and $mL \cdot kg\ LBM^{-1} \cdot min^{-1}$) and GE were calculated from the $\dot{V}O_2$ at the submaximal workload where the RER was closest to but not greater than 1.00 and this workload was consistent across observations within skiers. The GE was calculated as the ratio between PO and metabolic rate, where PO was calculated as the sum of the power exerted to overcome the rolling resistance and to elevate body mass and skiing equipment (m_{sys}) against gravity using the following equation:

$$PO\ [W] = vm_{sys}(g\ sin(\alpha) + \mu_R g\ cos(\alpha))$$

where g is gravitational acceleration, v is the treadmill speed ($m \cdot s^{-1}$), μ_R is the rolling resistance coefficient and α is the treadmill incline. Metabolic rate was calculated according to the equation introduced by Weir (29) as:

$$Metabolic\ rate\ [W] = \frac{4184(\dot{V}O_2(1.1RER + 3.9))}{60}$$

After a 5-min passive break a maximal TT test was completed, which involved a self-paced TT at a 7° incline and was 700 m for women (starting speed: 10 $km \cdot h^{-1}$) and 800 m for men (starting speed: 13 $km \cdot h^{-1}$). The skiers were able to adjust the speed by moving forwards and backwards on the treadmill by way of a laser system detecting their position (30). The speed of the treadmill increased by 0.19 $m \cdot s^{-2}$ and decreased by 0.11 $m \cdot s^{-2}$ as the skier moved to the front or rear of the treadmill, respectively. The highest consecutive 30-s $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ values were reported as peak values and the highest 5-s HR value was reported as peak HR (HR_{peak}).

Over the experimental period all equipment used for the roller-ski assessments was validated twice annually, prior to each test period. Treadmill speed was validated using an electronic tachometer (Lutron Electronic Enterprise CO, Taipei, Taiwan), while inclination was validated using a digital inclinometer (DNM 60 L Pro, Bosch GmbH, Germany). The AMIS system was validated against a mechanical lung simulator (Metabolic Simulator No 17056, Vacumed, Ventura, CA, USA) and custom-made Douglas bags. Relative concentrations and volumes of expired gas were analyzed using a MOXUS Metabolic Cart (AEI technologies, Bastrop, TX, USA) and a custom-built spirometer (Fabri AB, Spånga, Sweden). The AMIS system was also validated across a range of submaximal workloads corresponding to RER < 1.00 and $\dot{V}O_2$ 0.7–5.0 $L \cdot min^{-1}$. The typical error in $\dot{V}O_2$ values over the experimental period was calculated as < 0.1 $L \cdot min^{-1}$.

Training data

The skiers recorded their day-to-day training in a bespoke online training diary developed specifically for the Swedish Ski Association. An endurance training session was defined as a session containing at least 60 minutes of exercise and training intensities were categorized according to the 4-zone intensity scale developed by the Swedish Ski Association (31), with A1 = 60–74% of HR_{peak}, A2 = 75–84% of HR_{peak}, A3 = 85–95% of HR_{peak} and A3+ > 95% of HR_{peak} (32). The information recorded for endurance training included total training times in different activities (on-snow XC skiing, roller skiing, running, cycling, orienteering, ski-walking, or "other") and intensities (according to the four zones defined previously). The skiers allocated training time to each intensity zone using a modified session goal approach (33) based on the primary goal of the session and recordings from their personal HR monitors. Since the four zones are not defined by underlying physiological events (34) the binary model presented by Tønnesen et al. (35) was adopted for the purposes of this study. In this model, low-intensity training (LIT) refers to training intensities < 85% of the maximal HR (to approximate sub lactate threshold training) and high-intensity training (HIT) refers to training intensities ≥ 85% of the maximal HR (to approximate supra-lactate threshold training).

Statistical analyses

Data are presented as mean ± *SD* and the alpha level of 0.05 was set *a priori*. All analyses were conducted using Jamovi 1.0.7.0 (36) and SIMCA 16.0 (MKS AB, Umeå, Sweden). Prior to analyses, the Shapiro-Wilk normality test was employed to assess whether test variables were normally distributed. All anthropometric, physiological and training variables were observed to be normally distributed ($p > 0.05$), whereas FIS points were not ($p < 0.05$).

Changes in anthropometric and physiological variables, training volumes and FIS points, and any differences between sexes, were analyzed using linear mixed model (LMM) analyses. The models analyzed differences over the three specified years (2017, 2018 and 2019) and between sexes. LMM analyses were selected to account for the uneven distribution of women and men in the cohort, sex differences at baseline, and any missing data points. For anthropometric and maximal physiological test data and training volumes the LMMs were constructed with the variable being analyzed as the dependent variable, time and sex as factors, and skier ID as the cluster variable. As the submaximal roller-ski assessment protocols for women and men differed it was deemed inappropriate to compare submaximal physiological characteristics between sexes. For anthropometric, submaximal and maximal physiological test data and training volumes the LMMs also analyzed changes in anthropometric and physiological characteristics over time within sexes and independent of any sex comparisons. These within-sex models were constructed with the variable being analyzed as the dependent variable, time as the factor, and skier ID as the cluster variable. The package lme4 (37) in Jamovi (36) was used to fit the LMMs and *p* values were calculated using Satterwaite approximations (38). Standardized effect size (Hedge's *g*) analyses were used to interpret the magnitude of any differences over time within sexes. Effect size values are reported as eta squared and thresholds were set at: $g < 0.2$ trivial effect, $g = 0.2$ small effect, $g = 0.5$ medium effect, and $g = 0.8$ large effect (39).

Multivariate data analysis MVDA methods were used to analyze whether the skiers' best FIS points over the observational period could be predicted by anthropometric and physiological characteristics at the time of their best FIS ranking. MVDA methods were also used to examine whether changes in FIS points could be predicted by training volumes and changes in anthropometric and physiological characteristics. Prediction of best and change in FIS points were achieved using principle component analysis (PCA) and orthogonal projections to latent structures (OPLS). PCA and OPLS analyses were conducted on skiers' best FIS points and anthropometric and physiological characteristics were determined from the test period closest to their best FIS ranking. PCA and OPLS analyses were also conducted on absolute changes in FIS points, relative (%) changes in anthropometric and physiological characteristics and training volumes. Relative changes were used for anthropometric and physiological characteristics due to the large variations in absolute values between variables. Where possible, changes in FIS points and the associated relative changes in anthropometric and physiological characteristics were calculated from the first and final FIS points calculations over the 25-month period (i.e., 23rd March 2017 and 28th March 2019). This was achievable for 7 women and 10 men. However, since not all skiers were tested during all six designated test periods calculations were made between 23rd March 2017 and 22nd March 2018 for 6 women and 2 men, and between 22nd March 2018 and 28th March 2019 for 1 woman and 4 men. PCA was used to analyze the relationships between the anthropometric and physiological characteristics and training volumes and to assess any hidden structures and patterns via the reduction of data dimensions (40,41). OPLS was employed to identify linear relationships between three groups of variables: (1) FIS points; (2) anthropometric and physiological characteristics and; (3)

training volumes. Detailed information on MVDA methods has been published previously (40–44) and specific application of MVDA in the prediction of performance in winter sports has been documented by Nilsson et al. (19).

Predictions of best and change in FIS points (Y variables) were made using anthropometric and physiological characteristics and training volumes (X variables), with training volumes only modelled as X variables for predicting change in, and not best FIS points. R^2VY is the cumulative percent of the variation of the response explained by the model after the last component. R^2 is a measure of how well the model fits the data. R^2VYAdj is the cumulative percent of the variation of the response, adjusted for degrees of freedom, explained by the model after the last component. Q^2VY is the cumulative percent of the variation of the response predicted by the model, after the last component, according to cross-validation. Q^2 indicates how well the model predicts new data and permutations (21 for best FIS points and 24 for change in FIS points, one less cycle than number of X variables) of models were deemed valid if the intercept was < 0 or if all permuted Q^2 values were below the original model value. A useful model should have a large R^2 and Q^2.

To evaluate the importance of anthropometric and physiological characteristics and relative changes in the metrics and training volumes for predicting FIS points, variable influence on projection (VIP) analyses were executed. In an OPLS model, VIP summarizes the importance of the X variables, both for the X and Y models. VIP is normalized, and the average squared VIP value is 1; thus, a VIP > 1 indicates that the variable is important for the projection, and values < 0.5 indicate that the variable is not important for the projection. R^2 and Q^2 should be > 0.5 for well-modelled data (extract from the SIMCA-P + Handbook).

Results

The anthropometric characteristics of the participants recorded over the experimental period, together with the associated LMM statistics, percentage changes and Hedge's *g* are presented in Table 1. Whole- and upper-body lean mass increased over time in both men and women and a significant time × sex interaction for upper-body lean mass showed a greater increase in the women (2017–2019: 4.3%, medium effect) than the men (2017–2019: 3.8%, small effect). Significant time × sex interactions showed lower-body lean mass to increase over time in the women (2017–2019: 2.3%, small effect), and whole-body fat mass to decrease (2017–2019: 21.9%, large effect), while these variables were unchanged in the men (2017–2019: < 2%, trivial effects). Effects of sex were observed for all anthropometric characteristics, with men having greater stature, body mass, whole-body lean mass, upper-body lean mass, lower-body lean mass and BMI than women, whereas women exhibited greater whole-body fat mass than men.

Table 1 about here

The physiological characteristics of the skiers obtained via submaximal roller-ski assessments over the experimental period, together with the associated LMM statistics, percentage changes and Hedge's *g*, are presented in Table 2. Due to the different absolute workloads prescribed to the female and male athletes during the submaximal roller-ski assessments, sex comparisons and time × sex interactions were omitted from these analyses. Time effects showed the female skiers to achieve significant improvements in speed and $\dot{V}O_2$ at a BLa of 2 and 4 $mmol \cdot L^{-1}$ (2017–2019: 2.1–7.1%, all medium-sized effects).

Table 2 about here

The physiological characteristics of the skiers obtained via maximal roller-ski TT assessments over the experimental period, together with the associated LMM statistics, percentage changes and Hedge's *g*, are presented in Table 3. A significant time × sex interaction was present for $\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$), with an increase observed for the women (2017–2019: 5.6%, large effect) but not the men (2017–2019: 0.5%, trivial effect). Time effects analysed independently of sex comparisons showed the female skiers to achieve significant improvements in TT completion time (although LMM fit was poor, $R^2 = 0.227$), TT average relative PO and $\dot{V}O_{2peak}$ (in $L \cdot min^{-1}$ and $mL \cdot kg^{-1} \cdot min^{-1}$), while these variables were unchanged over time for the men. Effects of sex were observed for TT average relative PO and $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$ and $mL \cdot kg^{-1} \cdot min^{-1}$), with men exhibiting significantly greater values than women.

Table 3 about here

No significant time × sex interactions, or separate effects of time or sex, were observed for total, LIT or HIT training volume (all $p > 0.05$). Female skiers completed 660 ± 88 h of training in total (LIT: 602 ± 79 h; HIT: 58 ± 10 h) between test periods in 2017–2018 and 683 ± 87 h of training in total (LIT: 620 ± 78 h; HIT: 63 ± 11 h) between test periods in 2018–2019. Male skiers completed 689 ± 80 h of training in total (LIT: 620 ± 75 h; HIT: 69 ± 9 h) between test periods in 2017–2018 and 664 ± 88 h of training in total (LIT: 600 ± 76 h; HIT: 63 ± 13 h) between test periods in 2018–2019.

FIS distance and sprint points calculated over the experimental period, together with the associated LMM statistics, percentage changes and Hedge's *g* effect sizes are presented in Table 4. Whilst no time × sex interactions or sex differences were observed, distance points for women (2017–2019: 24.2%, large effect) and sprint points for both women (2017–2019: 48.6%, large effect) and men (2017–2019: 28.3%, medium effect) all improved significantly over the experimental period ($p < 0.05$).

Table 4 about here

Multivariate predictive models constructed using best FIS points and corresponding anthropometric and physiological data are presented in Table 5. The only valid predictive model was identified for best distance points in women. The regression coefficient of the underlying model for predicting new observations of best distance points in women and line of best fit are presented in Figure 1A. The importance of all anthropometric and physiological characteristics in predicting best distance points in women is presented in Figure 1B. Anthropometric variables identified as being important for projection (i.e., a VIP > 1) were total body mass, whole- and lower-body lean mass, stature, whole-body fat mass and BMI, while important physiological variables were speed and $\dot{V}O_2$ at a BLa of 2 and 4 $mmol \cdot L^{-1}$, $\dot{V}O_{2peak}$ and average sub-maximal $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$).

Table 5 about here

Figure 1 about here

Multivariate predictive models constructed using absolute change in FIS points, relative changes in anthropometric and physiological data and training volumes are presented in Table 5. Again, the only valid predictive model was identified for distance points in women. The regression coefficient of the underlying model for predicting new observations of changes in distance points in women and line of best fit are presented in Figure 2A. The importance of all anthropometric and physiological characteristics and training volumes in predicting changes in distance points in women are presented in Figure 2B. Anthropometric changes identified as being important for projection (i.e., a VIP > 1) were reductions in whole-body fat mass, BMI and total body mass, and increases in whole- and upper-body lean mass, while important physiological changes were increases in $\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1}), TT relative PO and $\dot{V}O_2$ and speed at a BLa of 2 and 4 mmol·L^{-1}

Figure 2 about here

Discussion

The present study has described the changes in anthropometric and physiological characteristics of male and female national development-team XC skiers over a 25-month period. The study also analyzed whether changes in these laboratory-assessed qualities and training volumes were predictive of changes in competitive performance, defined as FIS distance and sprint points. MVDA methods were employed, which facilitate the construction of robust predictive models that consider complex interactions between variables (40–44). Therefore, the findings provide an expansion of previous research that has employed correlational and multiple linear regression statistical approaches to predict XC skiing performance (i.e., based on FIS points) from laboratory-derived variables.

In terms of best FIS points over the 25-month period, the combination of anthropometric and physiological characteristics was able to predict FIS distance points in the female skiers. By contrast, the assessed variables could not predict distance or sprint points for the men, or sprint points for the women. This observation is contrary to a large body of previous work suggesting that distance and sprint XC skiing performance can be predicted from a range of laboratory-assessed anthropometric and physiological characteristics (3,9,10,12–15). The discrepancy in results is likely to be predominantly due to the MVDA methods (PCA and OPLS) employed in the present study, which differ from the simpler correlational and multiple linear regression analyses employed previously. MDVA randomly divides the modelled data into actual data (i.e. data collected from the skiers) and predicted data (i.e. model-predicted data), which allows correlated variables to be included in the predictive models, as statistical dependence is taken into account (43). This method allows robust predictive models to be constructed.

The anthropometric characteristics with a VIP > 1 and therefore considered important for the projection of distance points in women, were total body mass, whole- and lower-body lean mass, stature, whole-body fat mass and BMI. In the cases of stature, whole-body fat mass and BMI, jackknife uncertainty plots indicated that the variation in the influence of projection was large. As such, it is reasonable to conclude that the anthropometric characteristics consistently important for the projection of XC-skiing distance performance in the female athletes examined in the present study were total body mass and whole- and lower-body lean mass. Specifically, a body composition characterized by a low total mass but high levels of absolute lean mass appears conducive to successful distance skiing performance in women. Previous work has also indicated that whole-body lean mass is an important factor in female XC-skiing performance, albeit in sprint rather than distance events (13).

The physiological characteristics with a VIP > 1 and therefore considered important for the projection of distance points in women were speed and $\dot{V}O_2$ at a BLa of 2 and 4 $mmol \cdot L^{-1}$, $\dot{V}O_{2peak}$ and average sub-maximal $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$). However, jackknife uncertainly plots indicated that the variation in the influence of projection was large for $\dot{V}O_2$ at a BLa of 2 and 4 $mmol \cdot L^{-1}$. As such, it is reasonable to conclude that the physiological characteristics consistently important for the projection of XC-skiing distance performance in the female athletes examined in the present study were speed at a BLa of 2 and 4 mmol·L^{-1}, $\dot{V}O_{2peak}$ and sub-maximal $\dot{V}O_2$. These observations are supported by previous studies that have reported maximal aerobic power (3,12,13,17) and speed at a BLa of 4 mmol·L^{-1} (3) to be correlated with competitive race performance assessed by FIS distance points. Together with extensive previous research, these findings highlight the importance of a high lactate threshold, fractional utilization and maximal oxidative capacity in XC skiing.

As previously stated, sprint performance (as assessed by FIS sprint points) could not be predicted in women or men in the present study. This is likely attributable to the specific selection of physiological variables modelled as X (i.e., predictor) variables, as well as the specific roller-ski assessment protocol employed. For example, acceleration and maximal speed using double-poling have been identified as important determinants for classic XC sprint skiing performance (6,45) and these qualities were not examined or included as X variables in the multivariate models in the present study. Moreover, the roller-ski assessments in the current study were conducted using the diagonal-stride sub-technique on inclines of 3–7°, while double-poling performance on flatter terrain is likely more important during sprint races (14). As such, it is logical that variables obtained from double-poling roller-ski assessments conducted on flatter inclines and at higher speeds would be more reflective of classic sprint performance. Additional variables such as upper- and lower-body strength, technique, race tactics and pacing have also been identified as important factors in sprint skiing (6,45). These variables could be further investigated in relation to sprint XC skiing using similar statistical modelling methods as those employed in the present study.

A unique aspect of the present study was the longitudinal analysis of changes in skiers' physical qualities and the application of MVDA methods to examine whether these changes were predictive of competitive performance. Similar to the results for best FIS points, the combination of anthropometric and physiological characteristics, with the addition of training volumes, were able to predict changes in distance points in the female skiers (but not changes in distance or sprint points for the men, or sprint points for the women). The most important changes in anthropometric variables (i.e., a VIP > 1) for the projection of improved distance points in women were reductions in whole-body fat mass, BMI and total body mass, and increases in whole- and upper-body lean mass. However, for the increases in whole-body lean mass the jackknife uncertainly plots indicated that the variation in the influence of projection was large. Therefore, reductions in whole-body fat mass, BMI and total body mass, and increases in upper-body lean mass were the most important in terms of predicting improved competitive race distance performance in women. This is supported by previous studies suggesting that additional strength training and increasing lean body mass could result in improved XC skiing performance, particularly in women (46).

In terms of physiological developments, increases in $\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$), TT relative PO and $\dot{V}O_2$ and speed at a BLa of 2 and 4 $mmol \cdot L^{-1}$ were the most important changes (i.e., a VIP > 1) for predicting improvements in FIS distance points in women. These findings are supported by previous research showing aerobic capacity (3,12,13,17), speed at a BLa of 4 $mmol \cdot L^{-1}$ (3) and roller-ski TT performance (15) to correlate with competitive race performance. In the present study, GE was identified as being unimportant for predicting best or change in FIS distance points in female skiers (both VIP < 0.5 with large uncertainty), which is in contrast to previous research indicating that GE is an important predictor of performance in XC skiing (1,14,16). This discord is perhaps due to the different statistical methods employed, or may be a reflection of the differences in athlete sex or skiing event, whereby the aforementioned importance of GE has been observed in male sprint skiers (1,14,16). Furthermore, these earlier studies assessed GE for skate roller-skiing, which may be more similar to on-snow skiing than the diagonal-stride technique employed within the present study.

Unlike for the women, FIS distance points did not change significantly for the men over the 25-month period, which may explain the absence of a valid predictive model. This may be due to fewer female skiers competing in FIS distance events (47), which subjects female FIS points to greater change compared to male FIS points. Whilst both female and male skiers achieved improvements in FIS sprint points, these changes could not be predicted by changes in the athletes' anthropometric or physiological qualities. As alluded to previously, it is likely that the improved competitive performance in sprint events was attributable to other unmeasured variables. In addition, skiers can achieve substantial improvements in performance by simply using better equipment (i.e., faster skis) and services (i.e., a skilled waxing technician) (7,48).

Over the 25-month observational period female skiers achieved improvements in $\dot{V}O_2$ and speed at a BLa of 2 and 4 $mmol \cdot L^{-1}$, TT completion time and relative PO, and absolute and relative $\dot{V}O_{2peak}$, whereas male skiers achieved no such improvements in physiological qualities. Despite the physiological testing data indicating that the training performed by the women was more effective than that performed by the men, LIT, HIT and total training volumes were not different between the sexes. This is in contrast to previous research in junior XC skiers showing women to work at higher relative intensities than men within LIT sessions, perhaps in order to "keep up" with their male counterparts during mixed-sex training sessions (49). Although somewhat speculative, it is possible that the analyses of LIT, HIT and total training volumes in the current study were not sensitive enough to discern any true differences in training habits between the sexes, which could otherwise have explained the superior physiological improvements among the women. This possibility, including a systematic analysis of strength training, warrants further investigation.

The present study has some limitations, not least the relatively small sample sizes of 14 women and 16 men. This is a recurring issue in research with high-level athletes and the sample size in the present study is similar to that used previously with alpine skiers where MVDA methods were used to predict performance (19). Moreover, 10 elite skiers have previously been suggested to represent a normal sample size (3). This is largely due to the size of the populations, which in the present study comprised the Swedish national development team where all athletes (i.e., 100% of the available population) were recruited and included. An additional limitation is that all roller-ski assessments conducted over the observational period involved only the diagonal-stride classical skiing sub-technique. In contrast to this, competitive performance (i.e. FIS points) was derived from races using both classic and freestyle (i.e., skate) skiing, and all the related sub-techniques. Therefore, sub-maximal and maximal physiological characteristics specifically important to sub-techniques other than diagonal skiing would have been overlooked in the current models. It is also important to note that the results reported here are specific to the level and sex of the athletes (i.e., male and female national development-team XC skiers) and confined to the available laboratory-derived variables. It would, for instance, be of value to conduct similar analyses in senior-level elite XC skiers to determine whether the characteristics important for predicting performance differ between skiers of different ages and abilities. Furthermore, other variables not measured in the present study, such as maximal skiing speed and acceleration, upper- and lower-body strength, technique, race tactics and pacing should be included in future models for predicting changes in competitive performance. Also, whilst it was possible to rigorously quantify and analyze the skiers' endurance training (i.e., on-snow XC skiing, roller skiing, running, cycling, orienteering, ski-walking, and “other”), this level of detailed analysis was not possible for gym-based strength training as loads and volumes were not consistently recorded by the athletes/coaches. As such, any impact of specific strength training on changes in competitive performance should be further investigated.

A strength of the present study is the rigorous bi-annual validation of all laboratory equipment used in the roller-ski assessments. Changes in the skiers’ physiological qualities were assessed over a longitudinal period and it was imperative that these test data were valid and reliable, in order to accurately assess their influence on the projection of competitive performance. It was also important that these data enabled detection of any changes in skiers’ physiological capabilities. Few previous studies assessing long-term changes in physiological variables report the validation processes implemented over the experimental period.

The findings of the present study indicate that improvements in the body composition of developing female XC skiers are conducive to improved performance in distance events. As such, this should be reflected in female skiers’ development programmes (e.g., training prescription, nutrition support and education). Of course, any strategies to modify body composition should be overseen by appropriately qualified medical staff, dieticians and/or nutritionists. The most important physiological qualities for predicting both best and improvements in FIS distance points for women were $\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) and speed and $\dot{V}O_2$ at a BLa of 2 and 4 $mmol \cdot L^{-1}$, with improvements in TT relative PO also being important for the prediction of changes in FIS distance points. Practitioners supporting developing female XC skiers should consider the importance of these qualities when constructing both training interventions and physiological assessment strategies. Furthermore, the data presented here may indicate that development-level male skiers require greater training volumes to achieve improvements in physiological qualities than female skiers. These findings, together with the lack of valid predictive models for men, have implications for athlete selection and performance development.

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Conflict of Interest and Source of Funding

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Figure captions

Figure 1. A, Regression coefficient of the underlying model for predicting new observations of best FIS distance points in women including line of best fit; **B,** the importance of the X variables (anthropometric and physiological) for predicting Y (FIS distance points). Characteristics with VIP > 1 are most relevant for explaining Y. The plot is displayed with 95% jackknife uncertainty bars. AU = arbitrary units, BLa = blood lactate concentration, BMI = body mass index, HR = heart rate, LBM = lean body mass, PO = power output, TT = time trial.

Figure 2. A, Regression coefficient of the underlying model for predicting new observations of changes in FIS distance points in women including line of best fit; **B,** the importance of the X variables (percentage changes in anthropometric and physiological characteristics) for predicting Y (change in FIS distance points). Characteristics with VIP > 1 are most relevant for explaining Y. The plot is displayed with 95% jackknife uncertainty bars. AU = arbitrary units, BLa = blood lactate concentration, BMI = body mass index, HI = high-intensity, HR = heart rate, LBM = lean body mass, LI = low-intensity, PO = power output, TT = time trial.