
Modeling Oxygen Uptake during V1 Treadmill Roller Skiing

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ABSTRACT

Int J Exerc Sci 2(1): 48-59, 2009. The use of regression equations to predict oxygen uptake in relation to speed, grade, power output, and anthropometric characteristics is common in cardiac rehabilitation and athlete fitness testing. Research has suggested that sport specific testing improves the reliability of the test methodology and is appropriate for the development of effective training programs. This study focused on the development of a cross-country skiing specific predictor of maximal oxygen uptake based on treadmill speed, treadmill grade, gender, and body mass. This project simulated snow skiing on a large research treadmill using roller skis. A small sample size (N = 34) warranted the use of bootstrapping techniques and multiple regression analysis to develop a cross-country skiing specific model of oxygen uptake. The stability of each bootstrapped sample was confirmed via a cross-validation procedure. The equation of best resolve was: $VO_2 = -4.534 + 0.223(G) + 0.061(BM) + 0.139(TG) + 0.016(TS)$ in which G = Gender, BM = Body Mass, TG = Treadmill Grade, TS = Treadmill Speed. The resultant model can be used to design training programs, develop athlete fitness testing or research protocols, and to predict maximal oxygen uptake when sophisticated metabolic measurement equipment is unavailable.

KEY WORDS: Regression analysis, bootstrapping, cross-country skiing, oxygen consumption

INTRODUCTION

Precise measurement of oxygen uptake (VO_2) requires sophisticated laboratory equipment and considerable work effort by trained technicians. To alleviate the technical burdens associated with accurate measurement of VO_2 , several prediction equations have been developed for a wide variety of exercise modalities and population groups. Prediction models have been developed based on VO_2

measurements performed during running (5), walking (4), cycle ergometry (1-2, 8), step tests (13, 20), or arm cranking exercises (12, 21). Development of the above models was based primarily on lower body muscular work (1-2, 4-5, 8, 13, 20) or upper body muscular work (12, 21) individually. Muscular work in many sports is required from the upper and lower extremities at the same time in order to complete sport specific tasks. The non-synergistic characteristic of these exercise modes does

not accurately represent the full body kinetics of many sports including cross-country skiing. Furthermore, it has been suggested that sport specific testing methodologies might increase testing reliability (15).

Several seminal studies have detailed oxygen kinetics during cross-country skiing. These studies found good correlation between full body VO₂ measurements and competition performance requiring utilization of full body kinetics (14-15, 19). Mygind et al. (14) evaluated seasonal variations in highly trained cross-country skiers by analyzing VO₂ responses during both treadmill running and simulated double poling with an upper body ski ergometer. This group postulated that the muscles of the upper body consumed a high volume of oxygen and significantly contributed to an individual's VO₂.

Rundell (15) evaluated treadmill running and treadmill roller skiing. This study observed lower heart rates, VO₂max, minute ventilations, and accumulated blood lactates at maximal effort during treadmill roller skiing. Weight standardized VO₂max differed by 4 ml·kg⁻¹·min⁻¹, while absolute uptake differed by 0.25 L·min⁻¹ between the two tests (15). Watts et al. (19) also found physiological differences between double poling and pole-striding/diagonal striding. Significantly different peak VO₂ was measured during these two distinct styles of cross-country skiing. This previously presented data supported the use of full body exercises to evaluate VO₂ and physiological condition in cross-country skiers.

An accurate prediction model for cross-country skiing is not evident in the scientific literature. The purpose of this study was to develop a skiing specific VO₂ prediction model based on VO₂ measurements acquired during simulated skate cross-country skiing with roller skis on a motorized treadmill. The proposed model can be used to predict VO₂ based on anthropometric and workload information when laboratory tools, sensors, and highly trained, certified individuals are limitedly available.

METHOD

Participants

Thirty-four collegiate level cross-country skiers volunteered and signed an informed consent before participating in this study. The project's methodological design was reviewed and cleared by an internal review board prior to data collection. The study group consisted of 20 male and 14 female skiers. All skiers had significant treadmill roller skiing experience prior to data collection. This experience included many bouts of prolonged and high intensity roller skiing.

Protocols

Data collection occurred in October and November. Treadmill tests were conducted on an oversized research treadmill with belt dimensions of 3.5 by 2.5m (FitNex, Dallas, TX, USA). The subjects were allowed to acclimate to treadmill usage on the day of testing and volitionally expressed comfort during treadmill skiing prior to data collection. As a safety precaution, all skiers were attached to a ceiling mounted pulley system via rope and waist harness. This system was operated by a technician during

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all phases of treadmill use. Marwe Skating 610 roller skis (Marwe Inc., Hyvinkää, Finland) or V2 Aero 125 Skate Roller Skis (V2/Jenex Inc., Amherst, NH, USA), Exel C1 World Cup racing poles (Exel Sports NA, Winooski, VT, USA) with ground carbide tips specific for treadmill roller skiing, and Salomon SNS Pilot Boot/Binding system (Salomon SA, Metz-Tessy, France) were used throughout data collection.

The V1 skating technique was used exclusively during data collection and was shown in Figure 1. Briefly, the V1 technique is a skating technique used to climb hills or to traverse resistant snow conditions. The asymmetric application of pole and ski forces are the hallmark of this technique. The skier utilizes a poling motion on one side of the stride only. This poling action is accompanied by a propulsive force generated from an edged ski. After the force production phase of the stride the skier initiates a gliding phase, in which the opposite ski generates a lesser degree of force as the poles are retrieved to their initial position (16). The V1 technique was chosen for this analysis due to its use as a climbing technique. The grades from the middle portion to the end of the test, when maximum VO₂ values would be experienced, resembled hill climbing conditions. Previous research has indicated an advantage of using the V1 technique at a grade of approximately 5% or greater (11).

A Sensor Medics Vmax 29c Metabolic Measurement System (Yorba Linda, CA, USA) was utilized to collect and analyze all breath-by-breath spirometric data. The breath-by-breath data were collected continuously until volitional exhaustion.

The data were averaged every minute and the highest one-minute average occurring near the termination of the test was recorded as VO₂max. Between each test, the flow and gas sensors were calibrated. The flow sensor was calibrated using a 3.0 L manually operated pressure syringe per recommendation of the manufacture. The gas sensors were calibrated via three calibration gases of known concentration including ambient room air.



Figure 1. Sample of V1 skating technique during treadmill roller skiing including the technical setup to monitor VO₂.

Initially the treadmill was set to a two percent grade and was elevated by one percent every minute for the length of the test. The test was terminated when the

subject could no longer sustain the required work rate on the treadmill or when maximal effort was achieved. Maximal effort was defined for all tests in one of two ways: 1) the subject was no longer able to maintain pace and grabbed the safety bar at the front of the treadmill or 2) the scatter plot of VO₂ versus time developed a horizontal plateau lasting at least two minutes. The first criteria was the primary endpoint for most tests (N = 32).

Multiple treadmill belt speeds (162, 175, 188 or 200 m·min⁻¹) were utilized during testing, but each subject was tested at a single speed. Subjects were assigned a treadmill speed based on the speed required to achieve maximum effort during running VO₂max tests conducted less than 12 months before data collection. Subjects that achieved VO₂max at high running speeds were assigned to the two highest speeds in the present study; the converse was utilized for the slower runners.

Statistical Analysis

The VO₂max data were entered into an SPSS Version 14.0 (Chicago, IL, USA) data file as absolute and body mass relative values. Four independent variables were recorded for each subject. These predictors were treadmill roller skiing speed (m·min⁻¹) and grade (%), body mass (kg), and gender (1 = males, 0 = females).

The data were screened for outliers via Mahalanobis distances and were evaluated for the assumptions of normality (skewness and kurtosis), linearity and homoscedasticity (residual plots), and multicollinearity and singularity (tolerance and variance inflation factors) (18). After screening, the data were used in a

bootstrapping (7) regression analysis procedure with cross-validation. Prediction equations for estimation of VO₂ (L·min⁻¹) based on the aforementioned independent variables were developed by bootstrapping sub-samples (N = 24) iteratively extracting B coefficients via multiple linear regression. The independent variables were entered into the regression analysis in a single block.

The remaining samples (N = 10) were held out for a cross-validation procedure. Specifically, an equation based on the extracted unstandardized B coefficients was used to predict a VO₂max value for each sample in the cross-validation group. This value was compared to the actual measured VO₂max values acquired during the aforementioned data collection procedures. Paired T-tests, Pearson's Correlation Coefficients, and Standard Error of the Estimate (SEE) measurements were calculated to evaluate the extent of deviation between actual and predicted VO₂ values at maximal exertion. The entire process was automated via a Visual Basic (Microsoft, Redmond, WA, USA) program, scripted in the SPSS desktop environment. This process was iterated 100 times as higher numbers of iterations have not been shown to improve the descriptive capabilities of the analyses (7, 10). A Bland and Altman analysis was carried out on all pairs of data points to compare the actual and predicted data and to determine 95% limits of agreement (3). An alpha level of $p < 0.05$ was deemed significant for all statistical tests.

RESULTS

Anthropometric data are listed in Table 1.

Table 1. Demographic Information for Collegiate Level Cross-Country Skiers included in Bootstrapping Regression and Cross Validation Analysis (Mean±SD).

	Body Mass (kg)	Stature (cm)	Age (years)
Males	74.2±6.0	183±8	20±2
Females	59.4±7.1	169±6	20±2

Note: N_{males} = 20; N_{females} = 14

Tests for both univariate and multivariate outliers were conducted. The dataset was free of univariate outliers. With the use of Mahalanobis distance ($\chi^2 = 19.1$, $df = 4$, $p < 0.001$), a single multivariate outlier was identified. This individual was male and roller skied at 162 m·min⁻¹, the slowest treadmill speed used during data collection procedures. All other male subjects used treadmill speeds at least 26 m·min⁻¹ faster than this particular subject. Despite classification as a multivariate outlier, this subject was retained for analysis because the subject represented a realistic group of collegiate-level skiers at the lowest level of the performance spectrum.

The normality of the data was assessed via skewness and kurtosis. These values were between -1 and 1 indicating no significant deviation from a normal distribution. The data met the assumptions of linearity and homoscedasticity as indicated by the assessment of residual plots. Finally, both tolerance (1 - squared multiple correlations) and collinearity diagnostics

(variance inflation factors < 5.0) indicated freedom from multicollinearity and singularity.

Multiple regression analyses with cross-validation were iterated 100 times with a bootstrapping technique. All 100 regression calculations were statistically significant. To concisely report the relevant regression and cross-validation parameters, the following statistics are average values from the 100 iterations used to complete this project. The average *F* statistic for the regression computations was 34.1 and ranged from 19.8 to 73.0 (95% CI: 32.0 to 36.1). The average R² for analyses was 0.87 with an average adjusted R² of 0.84. The R² values ranged from 0.81 to 0.94 (95% CI 0.86 to 0.88).

Average unstandardized regression coefficients (B), standardized regression coefficients (β), t-statistics (t), significance levels (*p*), and partial correlations (*pr*²) are summarized in Table 2.

Table 2. Bootstrapped multiple regression analysis for prediction of VO₂ from treadmill speed, treadmill grade, body mass, and gender, data were averaged across 100 iterations and were reported as mean±SD.

	B	β	t	<i>p</i>	<i>pr</i> ²
Constant	-4.533±1.372	---	-2.68±0.99	0.07±0.16	---
Gender	0.223±0.223	0.123±0.126	0.68±0.54	0.53±0.25	0.15±0.12
Body Mass	0.061±0.009	0.660±0.094	5.10±1.27	0.003±0.016	0.74±0.09
Treadmill Grade	0.139±0.041	0.212±0.062	2.40±0.68	0.05±0.08	0.47±0.10
Treadmill Speed	0.016±0.006	0.232±0.091	1.92±0.78	0.13±0.17	0.39±0.14

Abbreviations: B, unstandardized coefficient; β , standardized coefficient; t, t-statistic; *p*, significance level; *pr*², partial correlation

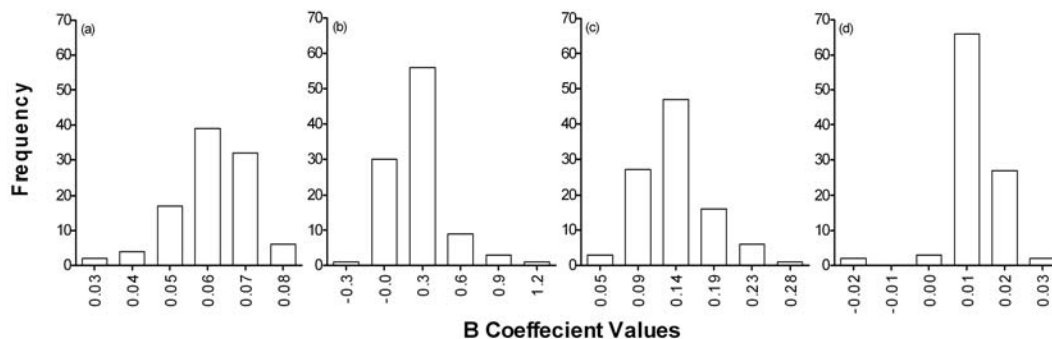


Figure 2. Histograms for B coefficients extracted during 100 reiterations of regression analysis. (a) Body mass, (b) gender, (c) treadmill grade, and (d) treadmill speed were the independent variables for 100 bootstrapped multiple regression analyses completed to extract B coefficients for the prediction of oxygen uptake in cross-country skiers (N = 24 per sample). Example: the B coefficient for body mass (a) ranged from 0.03 to 0.08 with a mode of 0.06 occurring in 39 of 100 regression computations.

Figure 2 depicts the B coefficient frequencies for each prediction parameter from each individual multiple linear regression computation. Each graph represents the number of times, out of 100, each B coefficient was extracted from a sample during the regression calculation.

The average Pearson’s correlation coefficient was significant (average R = 0.89, average *p* = 0.003) between actual measured and equation predicted VO₂max values in the cross-validation group. Paired samples t-tests indicated no significant differences between measured and estimated values (average *t* = 0.01, average *p* = 0.47). The SEE ranged from 0.0462 to 0.258 L·min⁻¹ with an average of 0.126 L·min⁻¹. The equation accurately predicted VO₂ during V1 treadmill roller skiing in collegiate cross-country skiers and displayed minimal levels of measurement uncertainty.

Figure 3 displays average measured versus predicted VO₂ values for the 100 cross-validation procedures. The abscissa in this figure represents the average measured VO₂ values for the 10 subjects used in each

cross-validation procedure; the ordinate represents the average predicted VO₂ values for the 10 subjects used in each cross-validation procedure. The Pearson’s correlation (*r*), standard error of the estimate, and sample size (*N*) from this analysis were listed.

The 95% limits of agreement between measured and predicted VO₂max values are shown in Figure 4 using the Bland-Altman Technique. The average difference between measured and predicted values was 0.00 L·min⁻¹ with upper and lower 95% limits of agreement of ± 0.28 L·min⁻¹ of oxygen consumed.

The following regression equation was derived from the averaged B coefficients extracted during analysis:

$$VO_2 = -4.534 + 0.223(G) + 0.061(BM) + 0.139(TG) + 0.016(TS)$$

In this equation, VO₂ was measured in L·min⁻¹, G = gender and was coded 1 = males and 0 = females, BM = body mass in kg, TG = treadmill grade in %, and TS = treadmill speed in m·min⁻¹.

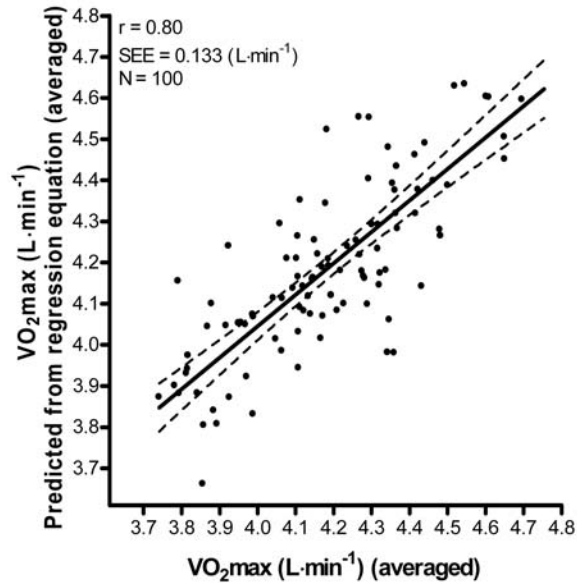


Figure 3. Plot of 100 cross-validation groups ($n = 10$ per group) of predicted $VO_2\text{max}$ values using regression derived B coefficients and the subject's body mass and gender and the treadmill's speed and grade at maximal effort versus actual measured $VO_2\text{max}$. Each data point represents a group-averaged value for the measured and predicted $VO_2\text{max}$ and dotted line represents a 95% CI, Pearson's correlation (r) and standard error of the estimate (SEE) were reported.

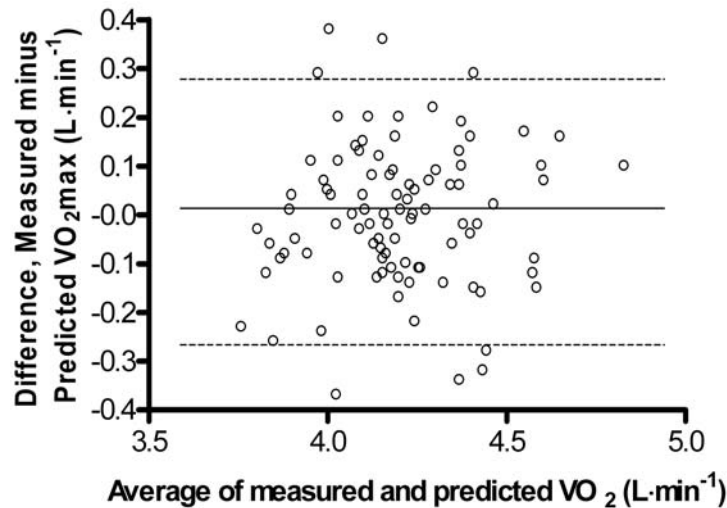


Figure 4. $VO_2\text{max}$ (L·min⁻¹): difference between measured and predicted $VO_2\text{max}$ versus average of predicted and measured values with 95% limits of agreement (dashed line) and mean difference (solid line) between the measured and predicted values.

DISCUSSION

A bootstrapping technique was used in combination with multiple regression and cross-validation via Pearson’s correlation, T-test statistics, and SEE measures to evaluate the capabilities of four predictor variables to estimate VO₂ in collegiate level cross-country skiers. The use of the bootstrapping technique was warranted because a small sample population was acquired for this project (7, 10). Limited subject availability for this style project was a necessary reality as both geographic and monetary constraints restrict access to a larger pool of highly trained cross-country skiers. Despite these limitations, the applied technique resulted in a high level of prediction accuracy. The model has both physiological and applicable significance for cross-country skiers training and performing at the upper levels of competition.

Body mass influenced VO₂ by a factor of 0.061 liters of oxygen consumed per kilogram of body mass. This relationship could potentially indicate that larger individuals have an aerobic advantage, however, the association, as depicted in Figure 5, is curvilinear with an upper limit at approximately 80 kg. The positive relationship represented in this model is valid between approximately 50 and 80 kg, but is lost with subsequent increases in body mass beyond this limit. This is an intrinsic limitation to the above-proposed equation. The equation will erroneously output greater VO₂ values when larger body mass values are entered into the equation.

Individuals exceeding the 80 kg threshold had the highest absolute VO₂max values. The differences in the rate of uptake were trivial compared to the VO₂max values of individuals with body masses 10 to 20 kg less. The relationship was even more

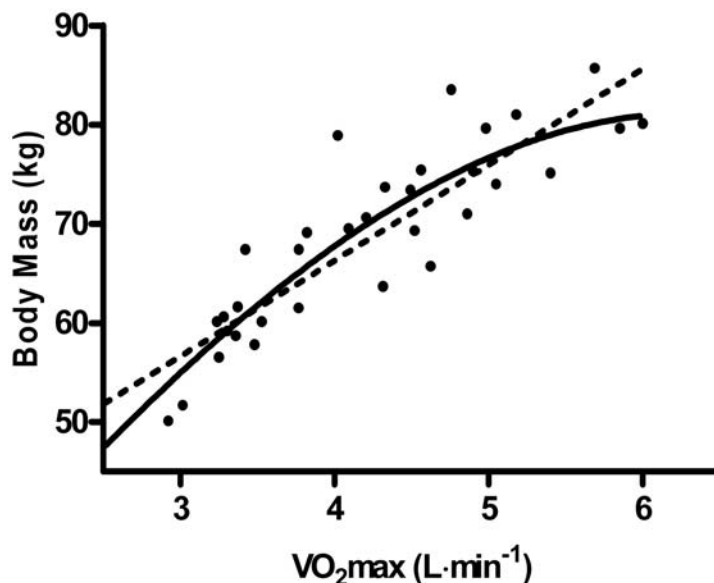


Figure 5. Association between oxygen uptake and body mass in cross-country skiers was curvilinear with a limit occurring around 80 kg. The dashed line represents the linear estimation and the bold line represents the curvilinear estimation of this association.

evident when VO₂max was expressed relative to body mass. Individuals weighing more than 80 kg had relative VO₂ values at or just below the mean for the sample population.

The grade of the treadmill had a profound, but expected affect on VO₂. As the treadmill grade was increased, VO₂ correspondingly increased by a factor of 0.139 L·min⁻¹. The majority of skiers reached maximal exertion when the treadmill grade was set between 10 and 12%. Eight individuals reached a maximum at either 8 or 9% (N = 4 for each grade). A single individual reached exhaustion at a 13% treadmill grade. Interestingly, of the eight individuals attaining maximal exertion at the 8 and 9% grades only one was female. The majority of female participants reached exhaustion at the 12% grade, which was expected partially due to differences in treadmill speed between the genders.

Kvamme et al. (11) suggested that most skiers regardless of experience level should transition from the V2 technique to the V1 technique at about a 5% grade due to a reduced economy during use of the V2 technique at slopes greater than this limit. The beginning portions of this protocol were below this crossover point and warranted the use of the V2 technique. In actuality, all skiers were requested to utilize the V1 technique for the whole tests. During the beginning stages of a test, using the V1 technique may alter the normal physiological response. However, by the time all skiers reached maximum effort they should have been using the V1 technique to maintain a reasonable cycle rate and stride length to keep pace with the treadmill belt speed. At least three minutes

would have elapsed prior to termination of the shortest tests (ending at 8% grades) allowing for adequate stabilization of a V1 related VO₂ response. Therefore, the effect of early use of the V1 technique below the crossover point was expected to be negligible.

Treadmill speed had a positive influence on VO₂ at maximal exertion. An increase in treadmill speed resulted in a 0.016 L·min⁻¹ per m·min⁻¹ change in an individual's predicted VO₂max. All females skied at 175 m·min⁻¹, while the majority of the males skied at 188 or 200 m·min⁻¹. Two males utilized treadmill speeds of 162 m·min⁻¹.

The use of gender specific speeds introduced a potential bias into the model. To investigate the effects of a speed and gender bias on this model, the amount of work performed at maximal exertion was estimated for each subject by calculating the product of speed and grade. In general, males skied faster but at lower inclines, while females skied slower but at greater inclines to elicit maximal exertion. Based on this estimation, there was no apparent work difference between genders. It appears that this gender bias was unnecessary to model the oxygen kinetics of a highly trained population of cross-country skiers. Inclusion of speed as a prediction variable may account for additional variance in the model, but it is likely this was shared with other parameters in the model.

Gender differences in the VO₂ response during maximal exertion have been suggested to favor males over females due to greater muscle mass and ability to generate greater amounts of power during endurance activities (17). The present

model supports the suggested advantage for males in endurance sports, however, nine out of 100 sub-samples used to derive the individual B coefficients had negative magnitudes indicating a favorable advantage for female athletes. More specifically, this negativity indicated a propensity for female subjects to have greater VO₂ values than their male counterparts included in these particular sub-samples. Several other sub-samples, as can be seen in Figure 1, regressed to a near zero effect for gender and indicated that trivial differences in gender are prevalent in this sample of highly trained skiers. Although the male gender has often been considered an advantage for aerobic endurance and oxygen utilization, some high level female athletes are now challenging this assertion. Hicks et al. (9) reviewed the potential mechanisms underlying the female advantage in fatigue resistance and suggested that this resistance was conferred via smaller muscle mass resultant in reduced vascular occlusion and oxygen demand during endurance exercise.

In the current model, body mass had the largest standardized effect on VO₂. The treadmill characteristics affected VO₂ to similar magnitudes, while gender had the smallest effect. Aside from the body mass limits described above and provided that the males within this cohort of subjects had the greatest body masses, the positive relationship between VO₂ and increased body mass might be explained by sex-related differences in muscle mass, hemoglobin concentrations, and cardiac output at maximal exertion (6). It is important to reiterate, however, that for some bootstrapped samples, gender differences were minimal. This suggests

that these physiological differences had trifling effects on VO₂max, were compensated for by other physiological mechanisms, or that several of the males included in the analysis had lower performance capabilities relative to a select number of female participants. Whatever the case may be, the proposed model is equally applicable for equipment-less aerobic capacity testing and training planning regardless of gender.

In order to elicit VO₂max, a ladder type protocol was used in which treadmill speed remained constant and grade was altered for an individual subject. Using the same protocol, coaches and athletes with access to a growing number of roller ski capable treadmills can estimate VO₂max without other expensive laboratory equipment or well-trained technicians. In addition to cost reduction gained through elimination of technician and metabolic analyzer costs, this protocol could be utilized in the field where similar terrain is available. It is important to confine testing to the current proposed model and to the limits partially outlined above. Each individual prediction parameter has noteworthy intrinsic limits.

Body masses in the original derivation population ranged from 49 to 86kg. Application of body masses above or below this range will result in increasingly erroneous estimations of VO₂. Treadmill speeds and grades ranged from 162 to 200 m·min⁻¹ and 8 to 13% respectively. The same extrapolation effect exists for these parameters. To derive the current model only four different speeds were used, however, speeds between 162 and 200 m·min⁻¹ not used to develop the model should predict VO₂ with a high level of

accuracy as the relationship between speed and maximal VO₂ appears linear. Finally, gender differentiation is of limited concern in a highly trained population because of the small estimated gender effect in this model. In some instances when evaluating high-level female skiers, differentiation based on gender may actually result in greater error and uncertainty.

The use of prediction models for treadmill running, walking, and roller skiing have limitations when used under conditions different from the conditions used during equation development. Inevitably, differences in metabolic analyzers, the recovered/rested status of a subject, and a subject's experience can influence the reliability of predicted VO₂ values. These are, however, intrinsic issues for predicting any physiological variable and not solely limited to the present equation. It is, therefore, essential for testing and variable measurement to be made under restrictive and precise conditions to reduce these effects.

The current model was developed specifically for the V1 technique. It has been shown previously (11, 14-15) that different skiing techniques elicit different physiological responses. A variable response between two techniques has also been shown at maximal exertion (19). Application of this model to a technique other than the V1 technique may produce invalid and uncertain results. Lastly, extension of these results to recreational (lower performance) or international (higher performance) populations may also produce invalid results. This application will also likely require alteration of the

treadmill protocol outside of the intrinsic bounds of the model.

In conclusion, the current model was developed using statistical techniques for small populations and performed well during cross-validation. It appeared that gender specific prediction models are less relevant in highly trained endurance athletes as differentiation added significant predictive capabilities less than 50% of the time. The derived equation can be used to predict oxygen uptake and for training planning purposes when skilled technicians and sophisticated equipment are not available. The equation produces estimates of VO₂max with minimal error as long as the model is applied within the specific limitations and tolerances.

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