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Research article

A Progressive 20m Shuttle Run Test to Estimate Maximum Oxygen Consumption in Ten Different Sports

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Abstract
Cardiorespiratory fitness is a fundamental determinant of both health outcomes and athletic performance, and is most objectively quantified through maximal oxygen uptake (VO_2max). Although laboratory-based graded exercise testing (GXT) with expired gas analysis remains the criterion method for VO_2max assessment, its practical application is limited by cost, equipment requirements, and the time needed to evaluate large groups. To overcome these limitations, the 20-meter multistage shuttle run test (20m-MST) has emerged as one of the most widely adopted field-based tools due to its simplicity and capacity for simultaneous group assessment. However, existing VO_2max prediction models based on the 20m-MST have largely been derived from small, sport-specific samples, limiting their generalizability to broader elite athletic populations. Therefore, the purpose of this study was to verify the validity of the 20m-MST and to develop a precise, field-applicable VO_2max prediction model for elite athletes across a wide range of ages, sexes, and sports disciplines. A total of 564 elite athletes (males = 336, females = 228; age range: 13 - 35 years) were recruited from 10 sports disciplines. Each participant completed both the 20m-MST and a laboratory-based maximal GXT with concurrent expired gas analysis, with a minimum interval of one week maintained between the two assessments. The GXT was conducted using the KISS Protocol, with VO_2max determined when at least two of five established physiological criteria were satisfied. Multiple regression analysis was conducted to develop a VO_2max prediction equation using shuttle run lap count, age, sex, and body weight as predictor variables, and both the intraclass correlation coefficient (ICC) and Bland-Altman analysis were employed to evaluate the reliability and limits of agreement between predicted and measured values. Correlation analysis revealed a statistically significant positive correlation between VO_2max and 20m-MST lap count across all subgroups ($r = 0.700$, $p < 0.001$). The regression model yielded a multiple correlation coefficient of $r = 0.833$, an explanatory power (R2) of 69.4%, and a standard error of estimate of 3.31 mL/kg/min. Validation demonstrated an ICC of $r = 0.901$, reflecting excellent agreement, with a mean difference of -0.031 ± 3.30 mL/kg/min and Bland-Altman limits of agreement of $-0.17 \pm 6.13\%$ (95% CI: -0.30 to 0.24). The 20m-MST involves progressively increasing speed with repeated directional changes, indicating that both aerobic and anaerobic energy systems contribute to performance, and shuttle run results should therefore be interpreted as a composite indicator reflecting VO_2max alongside agility and anaerobic capacity. The inclusion of age, sex, and body weight as predictor variables allows for VO_2max estimation across both sexes and a broad age range within a single unified equation, representing a substantial improvement over previously reported models derived from limited samples. The developed prediction model demonstrated excellent validity and reliability, providing a practical and accurate tool for the assessment of cardiorespiratory endurance in elite athletes. Future research should consider refinements to the shuttle run protocol and the incorporation of correction factors for anaerobic energy contributions to further enhance the precision of VO_2max estimation in diverse athletic populations.

Key words: VO_2max, shuttle run test, athletes, estimation equation.

Introduction

Improvements in cardiorespiratory fitness have been demonstrated to enhance oxygen transport capacity and utilization through increased mitochondrial enzyme activity (Woo et al., 2006), thereby producing beneficial effects in reducing the incidence and mortality associated with cardiovascular disease, overweight, and obesity-related conditions. Cardiorespiratory fitness extends beyond a simple health indicator, serving as a critical determinant of athletic performance across a wide range of sports disciplines. It refers to the body's capacity to absorb, transport, and utilize oxygen, and is generally expressed as maximal oxygen uptake (VO_2max) (Hardman and Williams, 1983; Levine, 2008). In particular, cardiorespiratory endurance in elite athletes is widely regarded as a fundamental physical fitness component with direct implications for competitive performance, and VO2max is the most universally employed objective measure for its assessment. Furthermore, elite long-distance runners are characterized by exceptionally high VO2max values, which are essential for superior race performance (Costill et al., 1973; Farrell et al., 1979; Saltin and Åstrand, 1967), and this measure is recognized as a pivotal physiological indicator for predicting athletic performance and evaluating the efficacy of training interventions.

Maximal oxygen uptake (VO_2max) can be measured through a graded exercise test (GXT) conducted on a treadmill or cycle ergometer (Åstrand and Rodahl, 1986), with the continuous analysis of expired gases until the subject reaches volitional exhaustion being regarded as the most ideal measurement protocol. However, laboratory-based assessments of this nature require expensive equipment and trained personnel, and their practical applicability is limited when evaluating large numbers of participants due to constraints in testing time and spatial requirements (Andersson et al., 2011; Cooper et al., 2005). Furthermore, maximal exercise testing is susceptible to the motivational level of the participant and may entail potential risks during the testing process, which poses challenges for its application in general populations or large-scale settings (Fitchett, 1985). For these reasons, alternative methods for estimate-

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ing VO2max utilizing submaximal exercise tests and various regression equations have been developed (Chatterjee et al., 2011; Chung et al., 2023).

To address the limitations inherent in laboratory-based testing, a variety of field-applicable methods for assessing aerobic capacity have been proposed (Åstrand and Ryhming, 1954; Burke, 1976; Ebbeling et al., 1991). Among these, the 20-meter multistage shuttle run test (20m-MST) has been widely adopted owing to its simplicity and efficiency. The test allows simultaneous assessment of multiple participants with minimal equipment and offers notable economic advantages in time and cost. The 20m-MST was originally developed by Leger and Lambert (1982) and has since been modified and refined for application across various age groups and populations (Ramsbottom et al., 1988; Boreham et al., 1990). Its incremental structure, in which participants repeatedly run 20-meter shuttles at progressively increasing speeds, allows natural attrition based on individual capacity, making it advantageous for safety and participant engagement. Compared to incremental exercise tests conducted on treadmills or cycle ergometers, the 20m-MST has been reported to demonstrate relatively low residual error (< 3%), and its validity has been substantiated by a correlation coefficient of approximately 0.71 with directly measured VO_2max (McNaughton et al., 1998; Cooper et al., 2005). Furthermore, multiple studies have reported high correlations (r = 0.90 - 0.93) between 20m-MST performance and VO_2max, thereby supporting its utility as a valid instrument for the assessment of aerobic capacity (Paliczka et al., 1987; Sproule et al., 1993).

The 20m-MST has been widely utilized for the evaluation of aerobic fitness and the prediction of competitive performance among athletes across a range of sports, including soccer, basketball, ice hockey, and combat sports (Paliczka et al., 1987; Köklü et al., 2011; Koropanovski et al., 2011; Aslan, 2013). It has also been reported as an effective tool for verifying the outcomes of training programs and monitoring physiological changes throughout the competitive season (Castagna et al., 2006; Geithner et al., 2006). Nevertheless, certain studies have noted potential limitations in the accurate prediction of VO_2max in specific populations, such as collegiate athletes. In particular, the margin of error associated with VO_2max estimation via the 20m-MST has been found to exceed 3% in individuals with higher cardiorespiratory fitness levels, prompting caution in its application within such populations (Grant et al., 1995; Ramsbottom et al., 1988). When the shuttle run counts obtained in the present study were entered into prediction equations reported in previous studies, the estimated VO_2max diffed from the directly measured VO_2max by 16% for the model of Léger et al. (1988), 5% for the model of Chatterjee et al. (2008), and 5.9% for the model of Mahar et al. (2006). Therefore, continued research is warranted to develop more precise VO_2max estimation models that preserve the convenience and practicality of field-based testing for elite athletic populations.

The development of estimation equations should be grounded in the magnitude of prediction error and the intended purpose of the equation. Moreover, when estimating VO_2max in elite athletes, accuracy, reliability, field applicability, and ease of measurement should be considered as primary criteria, taking precedence over safety concerns. Accordingly, the present study aims to verify the validity of the 20-meter multistage shuttle run test -a field-based assessment of cardiorespiratory endurance- and to explore effective evaluation methods, including the development of estimation equations, with particular consideration for elite athletes who are required to exert maximal cardiorespiratory capacity during competition.

Methods

Participants

This study was conducted at the Center for Sport Science in Incheon. 564 elite athletes (males = 336, females = 228, 13 - 35 years) were recruited for the present study. Athletes from Badminton (n = 14), Squash (n = 14), Soft tennis (n = 61), Rowing (n = 19), Soccer (n = 94), Canoe (n = 70), Taekwondo (n = 42), Tennis (n = 38), Field hockey (n = 100), handball (n = 112) were recruited. Those with cardiac, pulmonary, or inflammatory diseases or other medical contraindications were not included (Figure 1). All participants who agreed to participate in the study were given a description of the study to fully understand its purpose and the methods used in the ethical standards of the Declaration of Helsinki. In addition, all participants signed an informed consent form prior to participation. This study was approved by the University's Institutional Review Board for Human Subjects (1041459 - 202512-HR-016 - 01). The physical characteristics of the participants are shown in (Table 1).

Procedures

Upon the participants' initial visit to the testing facility, a medical history questionnaire was administered to assess their general health status, followed by anthropometric measurements. Body fat percentage was subsequently determined using bioelectrical impedance analysis (BIA; InBody 720, InBody Co., Korea). To verify the validity of the 20-meter multistage shuttle run test (20m-MST), each participant underwent both the 20m-MST and a maximal graded exercise test (GXT) with concurrent expired gas analysis, the latter serving as the criterion measure for

Table 1. Physical characteristics of the subjects. Values are means and SD.

		Age (years)	Height (cm)	Weight (kg)	Fat% (%)	BMI (kg/m^2)
Males (336)	Middle School Athletes (99)	14.6 ± 0.67	169.8 ± 7.64	58.6 ± 8.41	12.3 ± 3.44	20.2 ± 2.01
	High School Athletes (82)	16.4 ± 1.11	176.1 ± 7.31	72.7 ± 13.73	15.6 ± 4.76	23.3 ± 3.15
	Adult Athletes (155)	24.9 ± 4.35	179.5 ± 6.84	78.8 ± 9.06	17.1 ± 3.98	24.4 ± 2.08
Females (228)	Middle School Athletes (19)	14.2 ± 0.42	164.7 ± 5.45	60.9 ± 8.72	23.3 ± 5.28	22.4 ± 2.13
	High School Athletes (61)	16.2 ± 0.89	165.4 ± 6.63	62.8 ± 7.54	23.4 ± 3.54	22.9 ± 2.02
	Adult Athletes (148)	23.7 ± 3.12	166.1 ± 6.28	61.0 ± 5.95	24.6 ± 3.89	22.2 ± 1.99
Total (564)		20.3 ± 5.30	171.8 ± 9.02	67.4 ± 12.16	18.9 ± 6.11	22.7 ± 2.63

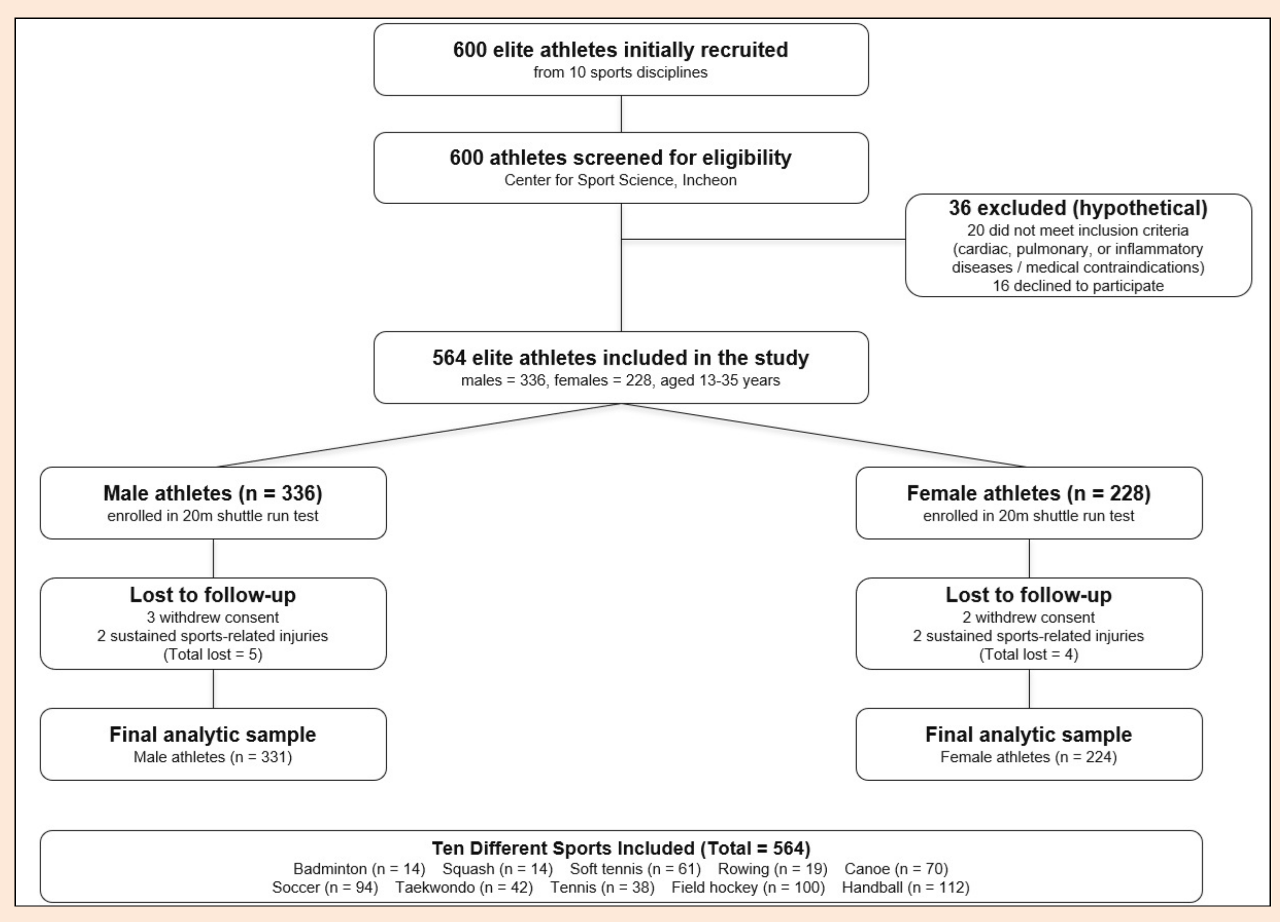


Figure 1. Participant flow chart.

cardiorespiratory endurance. To minimize any potential carry-over effects between the two assessments, a minimum interval of one week was maintained between the maximal GXT and the 20m-MST. The specific procedures and protocols for each test are described as follows.

Incremental exertion test (IET)

IET were performed on a 20-m shuttle run test (SRT). After completion of the preparatory exercise, the modified protocol was initiated at a speed of 8.0 km/h (speed of the 1st preparatory exercise) and was increased by 0.5 km/h incrementally. The test was stopped if the subject failed to reach the interior pylon prior to the "beep" on two successive occasions. Otherwise, the test ended when the subject stopped because of fatigue. Each subject was given encouragement to keep running as long as possible. Heart rate was recorded throughout the test using a Polar telemetry system. This protocol was designed to maintain an exercise duration of at least 15 min (Léger et al., 1988).

VO_2max direct measurements

The graded exercise test was measured using a treadmill and measured using the KISS-Protocol developed by the Korea Institute of Sports Science. KISS Protocol fixes the slope of the treadmill to 5 - 6%, the initial start speed is 90m/min, and the speed of 20 m/min gradually increases every 2 minutes. Termination criteria for the graded exercise test. VO_2max was considered to have been reached when at least two of the following five criteria were satisfied: (1) a plateau in oxygen uptake, defined as an increase in VO2 of no more than 150 mL·min-1 concurrent with the appearance of a steady-state; (2) a peak heart rate within 10 - 12 beats of the age-predicted maximum (220 - age); (3) a respiratory exchange ratio (RER) ≥ 1.15; (4) a rating of perceived exertion (RPE; Borg Scale) ≥ 17; and (5) a blood lactate concentration ≥ 8 mmol·L-1 (Pescatello, 2014). Oxygen intake and heart rate during exercise were analyzed with a fully automatic metabolic analyzer (Quark CPET, Cosmed, Italy).

In this study, maximal oxygen intake, maximal ventilation and maximal heart rate were selected for cardio respiratory function tests in athletes. The purpose of measurement was to evaluate and measure aerobic cardiopulmonary exercise capacity. Traditionally, measuring maximal oxygen intake is known as the best cardiorespiratory fitness measurement method used to indicate cardiorespiratory capacity for success during the first half and second half of an endurance sports event of more than 3 minutes. One of the most popular treadmill protocols is the Bruce protocol, known as the earliest standard treadmill test (Haff and Dumke, 2022). However, in this study, KISS (in South Korea) was used as the Graded Exercise Test (GXT) method, considering that the research subject was an elite athlete at the Korean national team level. When graded exercise load test, the subjects rested for 30 minutes before the GXT, and then the resting heart rate was checked using the Polar System, and the breathing gas was checked. An automatic respiratory gas analysis system (Quark series, COSMED Srl, Italy) was used as a variable device (George et al., 2007).

Statistical analysis

The mean and standard deviation are presented using the SPSS 23.0 statistical program for all variables measured in this study. Pearson's correlation coefficient between the number of 20 m shuttle run tests and the maximal oxygen consumption was calculated to confirm the validity of the 20 m shuttle run test according to sex and age. Multiple regression analysis was performed to develop a VO_2max predictive equation using the number of 20 m shuttle run tests, age, sex, and body weight. The values of the intercept, slope, coefficient of determination (R^2) and standard error estimate (SEE) were calculated. The absolute reliability between predicted VO2max and measured VO2max was calculated by the intraclass correlation coefficient (ICC). It was represented as poor (< 0.5), moderate (0.5 < 0.75), good (0.75 < 0.90), and excellent (> 0.90) reliability (Koo and Li, 2016). Furthermore, Bland-Altman analysis was performed to verify the correspondence between the directly measured results and the predicted results to confirm the consistency of the developed estimation equation, and limits of agreement (LoA), which is the ratio of the standard error and the average error in the calculated confidence interval, was calculated (%, LoA). The significance level of all statistical tests was set to 0.05.

Results

A total of 564 athletes completed both the maximal exercise test and the 20 m shuttle run test. Table 2 presents the correlation analysis results between maximal oxygen uptake (VO2max) and the number of 20 m shuttle run laps for each group. In male athletes, VO_2max showed a slight tendency to decrease with increasing age, whereas the number of shuttle run laps demonstrated an increasing trend. In contrast, female athletes showed no notable difference in VO_2max across age groups, while the number of shuttle run laps tended to decrease with age. To examine the validity of the 20 m multistage shuttle run test, a correlation analysis was conducted between the number of shuttle run laps and VO_2max. The results revealed a statistically significant positive correlation between the two variables across all subgroups stratified by sex and age. For the entire sample, the correlation coefficient between VO_2max and the number of 20 m shuttle run laps was r = 0.700 (p < 0.001).

Table 3 presents the results of the multiple regression analysis conducted to estimate VO_2max using predictor variables including the number of 20 m shuttle run laps, height, body weight, and age. The regression model yielded a multiple correlation coefficient of 0.833, with an explanatory power (R2) of 69.4%. The standard error of the estimate was 3.31 mL/kg/min, and the Durbin-Watson index was 1.618, indicating no significant autocorrelation among residuals. Table 4 presents the prediction equation developed to estimate VO_2max from the number of 20 m shuttle run laps in elite athletes. The intra-class correlation coefficient (ICC) between the measured and estimated VO_2max values was r = 0.901, indicating excellent agreement. The mean difference between the measured and estimated VO_2max was -0.031 ± 3.30 mL/kg/min (Table 4 and Figure 2B). The limits of agreement between the directly measured VO_2max and the values estimated from the 20 m shuttle run test were -0.17 ± 6.13% (95% Confidence Interval: -0.30 to 0.24).

Table 2. Correlation analysis between the VO_2max and the estimated value and reps of the shuttle run by sex and Age.

		VO_2max (ml/kg/min)	20m shuttle Run (reps)	r (p)	Predicted Value (ml/kg/min)	r (p)
Males (336)	Middle School Athletes (99)	59.3 ± 3.94	101.2 ± 13.46	.520 (< .001)	59.4 ± 2.30	.588 (< .001)
	High School Athletes (82)	57.8 ± 4.88	101.5 ± 12.50	.566 (< .001)	57.4 ± 3.15	.706 (< .001)
	Adult Athletes (155)	55.5 ± 4.30	102.8 ± 13.00	.596 (< .001)	55.8 ± 2.91	.634 (< .001)
Females (228)	Middle School Athletes (19)	49.5 ± 4.98	85.6 ± 14.15	.836 (< .001)	50.2 ± 3.27	.877 (< .001)
	High School Athletes (61)	50.4 ± 3.34	84.0 ± 14.31	.359 (< .01)	49.4 ± 2.63	.478 (< .001)
	Adult Athletes (148)	48.2 ± 3.88	82.9 ± 9.54	.512 (< .001)	48.6 ± 1.84	.505 (< .001)
Total (564)		53.8 ± 5.96	94.5 ± 15.36	.700 (< .001)	53.8 ± 5.96	.833 (< .001)

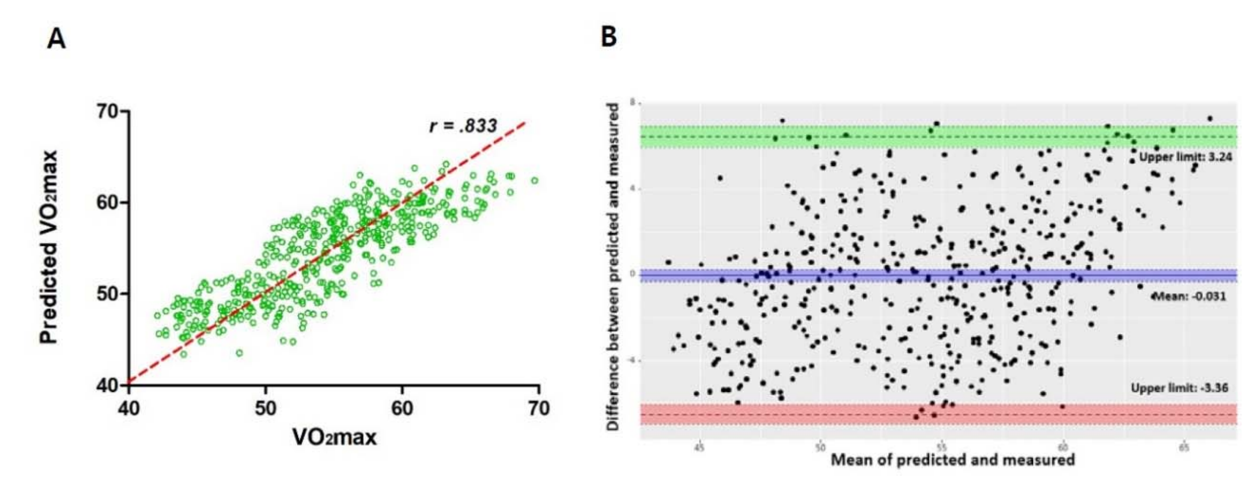
Values are means and SD; r = Pearson's correlation coefficient between VO2 max and estimated value and reps of the shuttle run.

Table 3. Multiple regression model to estimate VO_2max using a 20m shuttle run.

R	R^2	SEE	F	p	Durbin-Watson	
.833	.694	3.31	316.284	.000	1.618	
	Unstandardized Coefficients		**Standardized coefficients**	**p**	**Collinearity statistic**	
	β	**SEE**			**Tolerance**	**VIF**
Constant	45.487	1.306		.000		
20m shuttle run	0.168	0.011	0.432	.000	0.633	1.579
Sex	6.315	0.401	0.520	.000	0.503	1.989
Body weight	-0.131	0.014	-0.267	.000	0.660	1.516
Age	-0.120	0.030	-0.107	.000	0.781	1.280

Table 4. Equation for predicting VO_2max using a 20m shuttle run test.

	Equation	Predicted Value	Measured- predicted	ICC
n = 564	= 45.487+0.168 (20m SRT) + 6.315 (Sex; male 1, Female 0)-0.131 (Body weight)-0.120 (Age)	53.87 ± 4.97	-0.031 ± 3.30	.901



(A) and Bland-Altman limit of agreement (B) between the predicted and measured VO_2max values.

Figure 2. Correlation analysis.

Discussion

The purpose of this study was to develop an accurate VO2max prediction model for evaluating cardiorespiratory endurance and aerobic capacity in athletes using the 20 m shuttle run test, which can be readily applied in field settings. This study included a sufficient number of athletes (n = 564) for the development and validation of the prediction model. VO_2max values vary considerably according to age and sex. The correlation between measured and estimated VO_2max was highest among female middle school athletes (r = .877) and among male high school athletes (r = .706). Furthermore, the overall correlation coefficient across all participants was r = .833, indicating a relatively strong positive correlation. Accordingly, the proposed prediction model incorporates age, sex, and body weight as predictor variables, offering the advantage of estimating VO2max for both male and female athletes ranging from middle school to adult level through a single unified prediction model. Furthermore, based on the multicollinearity diagnostics and the statistical values of the standardized coefficients, the model was considered appropriate with no apparent issues regarding its adequacy. The agreement analysis between directly measured VO_2max and the values predicted by the 20 m shuttle run test equation indicated an overestimation of 3.24 mL/kg/min at the upper limit and an underestimation of 3.36 mL/kg/min at the lower limit. These values were within the acceptable absolute error range of 2 - 31% (You, 2011; Hopkins, 2000).

In the present study, the predictor variables included in the estimation equation were age, sex, number of 20 m shuttle run laps, and body weight (r = 0.833, SEE = 3.31 mL/kg/min). These predictors differed from those employed in previous studies that developed VO_2max prediction models using the 20 m shuttle run in athletic populations. Stojanovic et al. (2016) reported a prediction model based on 34 young basketball players, yielding a correlation of r = .65 with a substantial discrepancy between the directly measured VO_2max (55.45 ± 4.98 mL/kg/min) and the estimated value (48.91 ± 4.11 mL/kg/min). Similarly, St Clair Gibson et al. (1998) developed a VO_2max estimation equation using only 20 squash players, yielding r = .71. Other studies reporting estimation equations for athletic populations have involved sample sizes of fewer than 30 participants, which is considerably limited (Chatterjee et al., 2006; Kavcic et al., 2012). In contrast, the present study developed a VO_2max prediction equation based on 564 athletes across 10 different sports, encompassing a wide range of ages from middle school to adult level and including both sexes. Validation of the developed VO_2max prediction model revealed a significant correlation between the estimated and measured values (r = 0.901, SEE = 3.31 mL/kg/min). Bland-Altman analysis indicated that the mean difference between the directly measured and predicted VO_2max values was -0.031 ± 3.30 mL/kg/min. These findings suggest that the prediction model developed in this study may be useful for estimating VO_2max across male and female athletes of various age groups.

The 20 m shuttle run test employed in this study involves progressively increasing running speed in a repeated shuttle format, which suggests that not only aerobic capacity but also anaerobic energy contributions may play a complex role in performance. In particular, as the pace increases, athletes are required to perform rapid directional changes and re-accelerations at the end of each 20 m segment, which may increasingly engage the anaerobic energy system (Baker et al., 1993; Cooper et al., 2004; Holloway et al., 2008; Grant et al., 1995). Therefore, shuttle run performance should be interpreted as a composite indicator that reflects not only pure VO2max but also agility, explosive power, and anaerobic capacity simultaneously. These characteristics provide a rationale for the widespread use of the shuttle run test across various sports disciplines. In sports such as badminton (Ooi et al., 2009), soccer (Nassis et al., 2010), judo (Chaouachi et al., 2009), and taekwondo (Butios and Tasika, 2007), where both aerobic and anaerobic energy systems operate in an integrated manner, the shuttle run test is particularly useful in that it reflects exercise patterns similar to actual competition demands. However, individuals with relatively lower anaerobic power may produce underestimated results despite possessing equivalent aerobic capacity (Grant et al., 1995), which may serve as a limitation in the interpretation of test validity.

Furthermore, VO_2max estimation based on shuttle run lap counts may produce overlapping predicted values, as the same speed stage is repeated within certain intervals. This suggests that a simple lap count-based estimation approach may not adequately capture subtle inter-individual differences in performance capacity. Additionally, the repeated acceleration, deceleration, and directional changes inherent to the shuttle run format impose limitations on the application of conventional ACSM prediction equations that assume steady-state exercise conditions (Koutlianos et al., 2013), potentially leading to an underestimation of actual energy demands. Such discrepancies may result in inconsistencies between measured and predicted VO_2max values (Flouris et al., 2005; Leger and Lambert, 1982), highlighting the need for the development of more refined estimation models.

VO2max is influenced by a wide range of physiological factors. Sex, age, body composition, cardiac output, and hemoglobin concentration are among the primary determinants (Rowland et al., 2000), and cardiorespiratory function tends to improve alongside physical development during the growth period. The inclusion of sex in the prediction model of the present study may capture not only physiological sex differences in aerobic capacity but also differences in the biomechanical and neuromuscular characteristics involved in shuttle-run performance. The 20-m shuttle run requires repeated deceleration, 180° directional changes, and re-acceleration, and performance in this test is influenced by braking and propulsive forces, ground contact time, and running speed before and after the change of direction (Dos'Santos et al., 2021; Singh et al., 2024). Furthermore, sex-related differences in lower-extremity kinematic strategies during changes of direction have been reported (Donelon et al., 2024), indicating that such differences may partly influence the relationship between shuttle-run performance and VO_2max. According to the Fick principle, VO_2max is determined by cardiac output and the arteriovenous oxygen difference (Bassett, 2000), and long-term endurance training enhances these parameters through increases in cardiac size, improvements in oxygen-carrying capacity of the blood, and muscular metabolic adaptations. Physical activity level has also been reported as an important independent variable (Bruce et al., 1973), and the inclusion of such variables has been shown to significantly increase the explanatory power of prediction models.

Age was included in the prediction model of the present study to account not only for age-related differences in cardiorespiratory fitness during growth and maturation, but also for developmental differences in physical and neuromuscular performance capacity. Performance in the 20-m shuttle run varies with age, and large international studies have demonstrated clear age-related differences among children and adolescents (Lang et al., 2018). Moreover, the 20-m shuttle run requires not only aerobic capacity but also repeated acceleration and deceleration, 180° changes of direction, and re-acceleration, and these performance-related capacities, including change-of-direction ability, sprint performance, and muscular strength, have also been shown to develop throughout growth and maturation (Johansen et al., 2025). Furthermore, VO2max estimation has been reported to be more valid when individual characteristics such as age, sex, and body weight are considered alongside shuttle run performance rather than when shuttle run performance alone is used (Mayorga-Vega et al., 2015). Therefore, even among individuals with the same shuttle run performance level, the relationship with directly measured VO_2max may differ because of age-related differences in cardiorespiratory function and physical and neuromuscular characteristics. This provides an important basis for including age in a VO_2max prediction model.

Nevertheless, the 20 m shuttle run test continues to be widely used in field settings due to its practical advantages, including high reliability and validity, minimal equipment requirements, and the ability to assess large numbers of individuals simultaneously (Léger et al., 1988). Bland-Altman analysis has been established as a useful method for interpreting absolute agreement between measurements (Bland and Altman, 1986; Atkinson and Nevill, 1998), and the results of the present study were found to fall within an acceptable range of measurement error. However, given the structural limitations of the shuttle run test and the sport-specific nature of athletic performance, future research should consider adjustments to distance and speed increments, as well as the application of correction factors that account for the relative contribution of different energy systems, in order to develop more precise and accurate assessment methodologies.

Conclusion

The purpose of this study was to develop and validate a prediction model for estimating maximal oxygen uptake (VO_2max) in athletes using the 20-meter multistage shuttle run test (20m-MST) as a practical and field-applicable assessment tool. A single regression model incorporating age, sex, body weight, and shuttle run lap count was constructed based on a sample of 564 elite athletes representing a wide range of ages and sports disciplines. The model demonstrated a high correlation between measured and predicted VO_2max values ($r = .833$) with acceptable prediction accuracy (SEE = 3.31 mL/kg/min). Validation of the model further confirmed a strong criterion validity ($r = .901$) and an acceptable margin of error (-0.031 ± 3.30 mL/kg/min) between directly measured and estimated values. These findings suggest that the developed model constitutes a practical and valid assessment tool applicable to a broad athletic population ranging from middle school to adult-level athletes. However, it should be noted that the inherent characteristics of the 20m-MST, including potential contributions from anaerobic energy systems and the demands of repeated directional changes, may influence test performance and should be considered when interpreting the results. Accordingly, future research is warranted to develop more refined prediction models that account for sport-specific characteristics and the relative contributions of different energy systems, thereby further enhancing the precision and applicability of field-based VO_2max estimation in elite athletic populations.

Acknowledgements

The datasets generated during the current study are not publicly available but are available from the corresponding author upon reasonable request. The authors declare that they have no conflict of interest. All experimental procedures were conducted in compliance with the relevant legal and ethical standards of the country where the study was carried out. The authors declare that no Generative AI or AI-assisted technologies were used in the writing of this manuscript.

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Key points

- The model demonstrated a high correlation between measured and predicted VO_2max values (r = .833) with acceptable prediction accuracy (SEE = 3.31 mL/kg/min).
- Validation of the model further confirmed a strong criterion validity (r = .901) and an acceptable margin of error (-0.031 ± 3.30 mL/kg/min) between directly measured and estimated values.
- These findings suggest that the developed model constitutes a practical and valid assessment tool applicable to a broad athletic population ranging from middle school to adult-level athletes.

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