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Original paper

Prediction of $\dot{V}O_{2max}$ from a new field test based on portable indirect calorimetry

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Abstract

We assessed the validity and reliability of the new 15 m square shuttle run test (SST) for predicting laboratory treadmill test (TT) maximal oxygen uptake ($\dot{V}O_{2max}$) compared to the 20 m multistage shuttle run test (MST) in 45 adult males. Thirty participants performed a TT and a SST once to develop a $\dot{V}O_{2max}$ prediction model. The remaining 15 participants performed the TT and MST once and the SST twice for cross-validation purposes. Throughout testing $\dot{V}O_{2max}$ was determined via portable indirect calorimetry while blood lactate concentration was assessed at the fifth recovery minute. Comparisons of TT $\dot{V}O_{2max}$ (51.3 ± 3.1 ml kg^{-1} min^{-1}) with SST measured (51.2 ± 3.2 ml kg^{-1} min^{-1}) and predicted (50.9 ± 3.3 ml kg^{-1} min^{-1}) $\dot{V}O_{2max}$ showed no differences while TT blood lactate was higher compared to SST (10.3 ± 1.7 mmol vs. 9.7 ± 1.7 mmol, respectively). In contrast, MST measured (53.4 ± 3.5 ml kg^{-1} min^{-1}) and predicted (57.0 ± 4.5 ml kg^{-1} min^{-1}) $\dot{V}O_{2max}$ and blood lactate (11.2 ± 2.0 mmol) were significantly higher compared to TT. No test–retest differences were detected for SST measured and predicted $\dot{V}O_{2max}$ and blood lactate. It is concluded that the SST is a highly valid and reliable predictive test for $\dot{V}O_{2max}$.

Keywords: Cardiorespiratory fitness; Field test; $\dot{V}O_{2max}$; SST; MST

1. Introduction

Field (proxy) assessment of maximal oxygen uptake ($\dot{V}O_{2max}$) with minimal equipment and cost is valuable for epidemiological and field studies seeking information on cardiorespiratory elements associated with health-related fitness and performance enhancement as well as for exercise prescription and coaching.[1–4] Yet, current predictive models for bioenergetics suffer methodological limitations stemming primarily from inappropriate design.[5] A major weakness in the theoretical basis of proxies is the use of field measurements to predict laboratory-measured bioenergetics which, in turn, are used to provide information on actual (field) performance. Therefore, even minor differences in the exercise modes utilized in the validation procedures increase the potential for error and may have significant impact on the prediction of bioenergetics.[5]

A well-known proxy assessment for $\dot{V}O_{2max}$ is the 20 m multistage shuttle run test (MST) the validity of which, however, has been frequently questioned based, mainly, on metabolic [i.e., increased anaerobic contribution[1,2,6]] considerations. Our laboratory recently developed the 20 m square shuttle run test which was designed to reduce the turning angle during running from 180° to 90° and has demonstrated increased validity compared to the MST.[3,7–9] Yet, a considerable disadvantage of this test was that it required a 400 m^2 area (20 m side square). Therefore, in this paper we introduce the 15 m square shuttle run test (SST), a test suitable for any gymnasium large enough to incorporate a basketball court. The first objective of the present study was to generate a SST prediction model based on actual metabolic data collected during the test through portable indirect calorimetry in order to eliminate any effect of differences in the exercise modes utilized

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during the validation procedures (forward treadmill running vs. field running with slight turns). Additional objectives were to assess the criterion-related and construct validity as well as the test–retest reliability of the SST. Criterion-related validity was assessed through comparisons against its gold standard laboratory treadmill protocol. Construct validity was assessed by comparing the SST criterion-related validity against that of the classical MST, as well as through comparisons of the metabolic requirements of performing the two proxies and the reference standard laboratory test. Based on the previous findings from our lab we speculated that SST would be more accurate and reliable in predicting aerobic power that the conventional MST.

2. Methods

The experimental protocol conformed to the standards set by the Declaration of Helsinki and was approved by the ethical review board at the University of Wolverhampton. Forty-five healthy males aged from 18 to 29 (age: 21.3 ± 3.2 years; BMI: $23.1 \pm 2.0\,\mathrm{kg\,m^{-2}}$) volunteered and signed informed consent. Exclusion criteria included smoking and any muscular or skeletal injuries. The cohort was randomly divided into 'model' ($n = 30$) and 'validation' ($n = 15$) groups [no age, BMI or treadmill $\dot{V}O_{2max}$ difference between groups ($P > 0.05$)].

Within a 30-day period, participants in the model group underwent a treadmill test (TT) in the laboratory and a SST in a gymnasium. Within the same timeframe, participants in the validation group performed the TT and MST once, as well as the SST twice. Prior to data collection participants were familiarised with all assessment protocols and were advised to avoid stressful activities 36–48 h before visiting the lab. Tests were conducted at least four days apart and in a random order, by the same investigators and between 900 and 1200 h.

The TT was performed in the laboratory on a motorised treadmill (Powerjog, GXC200, UK) whereas MST and SST were performed in an indoor rubber-floored gymnasium. Speed throughout all protocols (i.e., TT, MST and SST) was adapted according to MST and the 20 m square shuttle test. The initial workload was set to $8.5\,\mathrm{km\,h^{-1}}$ with $0.5\,\mathrm{km\,h^{-1}}$ increments every minute. The MST was conducted according to known procedures[10] with workload being applied using the standard pre-recorded audio-CD and $\dot{V}O_{2max}$ predicted through the equation $\dot{V}O_{2max} = V_{max} \cdot 6.59 - 32.68$, where V_{max} (in $\mathrm{km\,h^{-1}}$) is the participant's maximal velocity at the final stage of the test. For the purposes of the present paper, this equation was coded as EQ_{MST}.

Workload during the SST was regulated using a pre-recorded protocol written in an audio-CD emitting tones at appropriate intervals for a 15 m course. During the SST execution, participants had the choice of running throughout the test either clockwise or anticlockwise on the sides (15 m) of a square marked on the gymnasium's floor. Cones were placed inside and outside of the four corners of the square, to ensure running on course. Individuals were advised to perform wide turns to avoid disturbances in their running technique and were encouraged, particularly at the latter stages of the test, to reach volitional exhaustion. Each participant started the test at one of the corners and followed the prescribed pace which meant that he had to complete one side of the square and be at the next corner in synchrony (i.e., ± 1 s) with the next sound signal. Testing was terminated when participants could no longer maintain the prescribed pace for two consecutive signals.

Throughout all three tests the participants ran individually and inspired room air through a facemask having their pulmonary ventilation continually monitored by a $K4b^2$ (Cosmed, Rome, Italy) portable metabolic cart. Oxygen uptake ($\dot{V}O_2$, in $\mathrm{ml\,kg^{-1}\,min^{-1}}$) was measured via open circuit spirometry. Flowmeter and gas analysers were calibrated with a 2-l syringe and standard gasses prior to each data collection. Special care was taken in maintaining similar environmental conditions in both measurement sites during assessments (ambient temperature and humidity at 29 °C and 40%, respectively). Heart rate was monitored through short-range telemetry with a Polar S810 (Kempele, Finland). $\dot{V}O_{2max}$ was confirmed only when maximal heart rate was greater than $185\,b\,\mathrm{min^{-1}}$ and the respiratory quotient was greater than 1.1.

At completion of each $\dot{V}O_{2max}$ assessment, participants remained seated and 10 μl of capillary blood were taken from the fingertip of the 4th finger (ring finger) at the 5th minute of recovery to determine blood lactate concentration. The sample was collected in a disposable calibrated non-heparinised capillary tube and was immediately put into reagent solution for subsequent analysis by photometric method (Miniphotometer plus LP 20, Dr. Lange GmbH, Berlin, Germany).

Sample size calculations were conducted based on values from our original SST experiment.[7] The adopted repeated measures randomised-block design incorporating two groups (model and validation) of minimum 15 participants being measured twice achieved a 95% power when an F test was used to test the groups factor at a 5% significance level. Using data from the model group ($n = 30$), a simultaneous linear regression analysis was introduced to construct a model (EQ_{SST}) predicting $\dot{V}O_{2max}$ measured during the SST through the portable analyser using V_{max} as an independent variable. Thereafter, a second regression model (EQ_{TT}) was generated for predicting $\dot{V}O_{2max}$ during the TT (dependent variable) using the EQ_{SST} predicted values as an independent variable in order to account for any variation in energy cost between the two exercise modes (i.e., TT and SST).

Data from the validation group ($n = 15$) were used to assess the criterion-related and construct validity of EQ_{MST}, EQ_{SST}, and EQ_{TT} as well as to examine and compare the metabolic requirements of performing the three protocols. In addition, the SST test–retest data from this group were used to assess SST test–retest reliability. Correlation coefficients, analysis of variance (ANOVA), 95% limits of agreement analysis and percent coefficient of variation were used for both validity

Table 1
Uni-variate statistics (mean ± SD) and linear regression analyses for predicting $\dot{V}O_{2max}$ during the SST and the TT in the model group ($n = 40$).

	$_{Ind}$Variable	$_{Dep}$Variable	R^2	SEE	F	$\dot{V}O_{2max}$	$\dot{V}O_{2max}$	r
EQ_{SST}	V_{max}	$\dot{V}O_{2max}$	0.82	2.71	130.4*	49.6 ± 5.8	49.6 ± 6.6	0.91*
EQ_{TT}	EQ_{SST}	$\dot{V}O_{2\,max}$	0.71	3.31	67.9*	51.3 ± 2.9	51.3 ± 3.7	0.86*

Note: Non-significant ANOVA between $\dot{V}O_{2max}$ and $\dot{V}O_{2\,max}$ ($P > 0.05$).
Key: $EQ_{SST,TT}$ = calculated regression models to predict SST and TT $\dot{V}O_{2max}$, respectively; $_{Ind}$Variable = independent variable; $_{Dep}$Variable = dependent variable; R^2 = coefficient of determination; SEE = standard error of the estimate; F = ANOVA F statistic; $_P\dot{V}O_{2max}$ mean predicted value using the calculated models (ml kg^{-1} min^{-1}); $_M\dot{V}O_{2max}$ mean measured value measured during testing (ml kg^{-1} min^{-1}); r = correlation coefficient between actual and predicted values; V_{max} = speed at SST (km h^{-1}); $_{SST}\dot{V}O_{2max} = \dot{V}O_{2max}$ measured during the SST (ml kg^{-1} min^{-1}); $_{TT}\dot{V}O_{2max} = \dot{V}O_{2max}$ measured during the TT (ml kg^{-1} min^{-1}).
* Person's coefficient significant at $P < 0.001$.

Table 2
Results (mean ± SD) and comparisons of the different models for predicting TT $\dot{V}O_{2max}$ and SST test–retest reliability in the validation group ($n = 15$).

	$_P\dot{V}O_{2max}$	$_M\dot{V}O_{2max}$	Time (min:sec)	BL_{LAC} (mmol)	LIM_{AG} (ml kg^{-1} min^{-1})	Percent CV
TT	51.3 ± 3.1	18:03 ± 2:19	10.3 ± 1.7	–	–	
MST	53.4 ± 3.5*,†	57.0 ± 4.5*,†	9:44 ± 1:10*,†	11.2 ± 2.0*,†	2.1 ± 4.6	4.4
SST_1	50.9 ± 3.3	51.2 ± 3.2	12:50 ± 1:36*	9.7 ± 1.7*	−0.4 ± 3.0	3.0
SST_2	50.9 ± 2.7	50.9 ± 3.3	12:41 ± 1:42*	9.4 ± 1.6*	−0.01 ± 1.9	1.9

Key: $_P\dot{V}O_{2max}$ mean predicted value using the calculated models (ml kg^{-1} min^{-1}); $_M\dot{V}O_{2max}$ mean measured value measured during testing (ml kg^{-1} min^{-1}); time = exercise time; BL_{LAC} = blood lactate; LIM_{AG} = 95% limits of agreement; percent CV = percent coefficient of variation SST_1 = first SST trial; SST_2 = second SST trial.
* Significant ANOVA between TT and either MST or SST at $P < 0.001$.
† Significant ANOVA between MST and SST $P < 0.001$.

and reliability according to known procedures.[11] The level of significance was set at $P < 0.05$.

3. Results

Routine pre-analysis screening procedures were used to assess whether the model-group data conformed to the assumptions of linear regression analysis. Although normally distributed, the variables used in these analyses were not independent from one another. Examination of residuals scatterplots detected no violation of normality, linearity, and homoscedasticity between predicted $\dot{V}O_{2max}$ scores and errors of prediction. Mahalanobis distance of each case to the centroid of all cases detected no multivariate outliers for $\chi^2 < 0.001$. Table 1 depicts relevant statistics for the resulting prediction models:

$$[EQ_{SST}]\dot{V}O_{2max} = V_{max} \cdot 3.69 - 3.01$$

$$[EQ_{TT}]\dot{V}O_{2max} = EQ_{SST} \cdot 0.88 + 5.32$$

Thus,

$$[EQ_{TT}]\dot{V}O_{2max} = (V_{max} \cdot 3.69 - 3.01) \cdot 0.88 + 5.32$$

Cross-validation results based on the validation-group data appear in Table 2. ANOVA demonstrated that measured ($P < 0.001$) and predicted ($P = 0.004$) MST $\dot{V}O_{2max}$ were significantly different than TT $\dot{V}O_{2max}$ as well as measured ($P < 0.001$) and predicted ($P < 0.001$) SST $\dot{V}O_{2max}$. In contrast, measured ($P = 0.650$) and predicted ($P = 0.430$) SST $\dot{V}O_{2max}$ were similar to TT $\dot{V}O_{2max}$ (Fig. 1). The TT correlated with measured and predicted MST $\dot{V}O_{2max}$ at $r = 0.72$ ($P < 0.001$) and $r = 0.68$ ($P < 0.05$), as well as with measured and predicted SST $\dot{V}O_{2max}$ at $r = 0.92$ ($P < 0.001$) and $r = 0.87$ ($P < 0.001$), respectively. Based on the calculated limits of agreement, a TT $\dot{V}O_{2max}$ value of 40 ml kg^{-1} min^{-1} would be predicted using the MST to be as low as 37.5 ml kg^{-1} min^{-1} (i.e., 40 + 2.1 − 4.6), or as high as 46.6 ml kg^{-1} min^{-1}. For the same scenario, the SST prediction would range between 42.6 and 36.6 ml kg^{-1} min^{-1}.

Test–retest SST reliability results appear in Table 2. No statistically significant differences where detected between test–retest measured and predicted $\dot{V}O_{2max}$ as well as exercise time and blood lactate concentration.

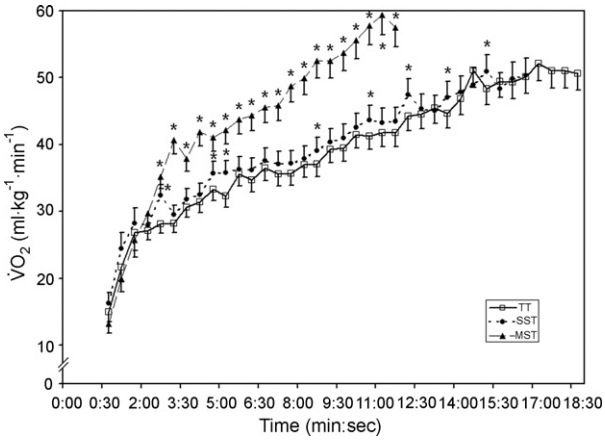

Fig. 1. Mean measured $\dot{V}O_{2max}$ values during the three protocols in the validation group ($n = 15$). Asterisks indicate repeated measures ANOVA statistically significant ($P < 0.001$) differences against TT.

The test–retest correlation coefficients for measured and predicted $\dot{V}O_{2max}$ were $r = 0.78$ ($P < 0.001$) and $r = 0.92$ ($P < 0.001$), respectively. Based on the calculated limits of agreement, a SST $\dot{V}O_{2max}$ value of 40 ml kg^{-1} min^{-1} would be predicted on a different occasion to be as low as $40 + 0.01 - 1.9 = 38.1$ ml kg^{-1} min^{-1}, or as high as 41.9 ml kg^{-1} min^{-1}.

4. Discussion

The present results showed that the new SST is a highly valid and reliable test for predicting $\dot{V}O_{2max}$ derived through a laboratory treadmill test. Regarding criterion-related validity, no differences were detected for both measured and predicted $\dot{V}O_{2max}$ between SST and TT confirming that the energy demands of the two tests were similar. In addition, the SST limits of agreement were narrow and well accepted.[11] These results confirm previous studies from our group showing that the validity of proxies is increased by designing tests that closely simulate the laboratory protocol used as reference standard.[5,7–9]

From a construct-validity perspective, the SST was found to be a valid proxy of the TT since no differences were detected in blood lactate between the two tests. In contrast, the MST demonstrated significantly increased measured and predicted $\dot{V}O_{2max}$ and blood lactate values compared to TT and SST, as well as wider limits of agreement. These findings agree with previous studies reporting significant bias between the TT evaluation of $\dot{V}O_{2max}$ and its prediction via the MST,[6,12,13] attributed mainly to metabolic[1,2,6] factors. Our results are also in line with the findings of a previous study[1] reporting that, at the same level of effort, the MST is accompanied by increased lactic acidosis not found in either running on a treadmill or performing a progressive track test involving conventional forward running. This increased blood lactate concentration is attributed to a greater metabolic stress possibly caused by the biomechanical complexities associated with the 180° turn in shuttle running (continuous cycles of acceleration, deceleration and change in direction) resulting in significant vertical displacement of the centre of mass and reduced stride efficiency.[14] Consequently, it may be that the present increased MST $\dot{V}O_{2max}$ compared to SST was attributed to the difference in the vertical lift work of the body, which was more economical in the SST given the lower $\dot{V}O_2$ required to run at the same velocity.

It is concluded that the SST is a highly valid and reliable predictive test for human bioenergetics. It is an advanced proxy assessment with a strong predictive capacity based on actual metabolic data collected during the test through portable indirect calorimetry. In addition, it is a comparatively practical test suitable for any gymnasium large enough to incorporate a basketball court. Future studies should aim in further validating the SST by measuring larger samples of participants and generating different prediction models for various groups of individuals.

Practical implications

- The recently-developed 20 m square shuttle run test is a valid field assessment tool for cardiorespiratory fitness but it is limited due to the 400 m^2 area required to conduct it.
- In this paper we introduce the 15 m square shuttle run test, a test suitable for any gymnasium large enough to incorporate a basketball court.
- The new test represents an advanced fitness assessment tool because its prediction equation was based on actual metabolic data collected during the test through portable indirect calorimetry.
- Based on comprehensive validation procedures, we found that the 15 m square shuttle run test is a highly valid and reliable predictive test for maximal oxygen uptake.

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