TITLE
A comparative analysis of two novel shuttle running field tests for critical velocity modelling in football players

AUTHOR
Amzaleg, Simon E.; Patterson, Stephen D.; Coakley, Sarah L.

JOURNAL
Journal of Elite Sport Performance

DATE DEPOSITED
18 April 2023

Title: A comparative analysis of two novel shuttle running field tests for critical velocity modelling in football players

Amzaleg, Simon.E[1]., Patterson, Stephen.D[1]., and Coakley, Sarah.L[1].

Centre for Applied Performance Sciences, Faculty of Sport, Allied Health & Performance Sciences, St Mary's University, Twickenham, UK.

ORCID:

Simon Amzaleg – 0000-0003-0852-7010

Stephen Patterson - 0000-0003-4667-9939

Sarah Coakley – 0000-0002-9314-1392

✉Address for correspondence:

Dr Sarah Coakley,

St Mary's University Twickenham,

Twickenham,

TW1 4SX

UK

Tel: 0208 240 4316

Email: Sarah.Coakley@stmarys.ac.uk

Abstract

Background and aim: The study compared differences in derived critical velocity (CV) and maximal speed from the 3-Minute All-Out Shuttle Test (3MST), 7-Minute Intermittent Critical Velocity Shuttle Test (7MST) and 3-Minute All-Out Running Test (3MRT). We also determined test-retest reliability of the 3MST versus the 7MST. **Methods:** Eleven semi-professional football players completed 10 visits; 3 familiarisation and 7 testing sessions (3 trials for each of the 3MST and 7MST and 1 trial of the 3MRT). CV was calculated, and maximal speed was recorded via GPS. **Results:** CV via the 3MRT (14.17 ± 1.49 $km.h^{-1}$) was faster than the 3MST (10.12 ± 0.97 $km.h^{-1}$, $p < 0.001$) and 7MST (9.03 ± 0.97 $km.h^{-1}$, $p < 0.001$), although minimal differences were observed between the 3MST and 7MST ($p = 0.13$). Maximal speed differed across all test modes; 3MRT (29.07 ± 2.19 $km.h^{-1}$, $p < 0.001$), 3MST (26.18 ± 1.71 $km.h^{-1}$, $p < 0.001$) and 7MST (23.14 ± 1.10 $km.h^{-1}$, $p < 0.001$). Intra-class correlation coefficient was larger for the 3MST (0.37) than the 7MST (0.05). Coefficient of variation was smaller for the 3MST (7.57%) compared to the 7MST (11.56%). **Conclusions:** Shuttle tests derive significantly slower CV and maximal speeds compared to linear tests and thus likely provide greater task specificity for CV modelling of team-sport athletes.

Key Words: HIGH-SPEED RUNNING, TEAM-SPORT, FATIGUE, THRESHOLD.

INTRODUCTION

Time-motion analyses suggest that successful performance in competitive football is correlated to the quantity of high speed running and change of direction [1–3]. This is a trend indicative across team-sports [4], whereby contemporary match tactics have increased the intermittent demand of quickly changing energy requirements from non-severe to severe metabolism [5]. Modelling the critical point of this energetic interaction is imperative for profiling team-sport athletes, to help inform training, competition and tactical decisions [6]. Clinical and field graded exercise tests estimate maximal capacity through tolerance to incremental workload [7], which negates the identification of a critical work rate between sustained and un-sustained metabolism, suggesting graded exercise tests are non-specific and possibly outdated for analysing the unique energetics of contemporary intermittent performance.

The 3-Minute All-Out Running Test (3MRT) is a short, linear-run test, adapted from seminal critical power methods. The 3MRT provides valid and reliable estimates of critical velocity (CV) by modelling a hyperbolic relationship between running speed and time [8,9]. The asymptote identifies a CV, above which a finite distance capacity (*D´*) is estimated to differentiate severe and non-severe metabolism [10]. The relationship between these mechanisms allows for subsequent calculations of competition pacing strategies and high-intensity interval training (HIIT) prescription [11,12].

The CV concept is less tolerated when applied to intermittent compared to constant velocity exercise, meaning lower CVs and higher *D´*s are estimated via intermittent running [13,14]. This highlights the importance of task specificity for CV estimation and is conceivably exacerbated in team-sports due to the metabolic cost of high-speed running and changes of direction [14–16]. Shuttle running provides an exercise modality that matches the biomechanical demands of intermittent sports [17]. Examples of shuttle running CV methods include, the 3-Minute All-Out Shuttle Test (3MST) and 7-Minute Intermittent Shuttle Test (7MST).

The 3MST is adapted from the 3MRT, however, it is run over a defined shuttle distance rather than uninterrupted running and is well validated for estimating CV [18]. Several studies have established differences in CV between the 3MRT and 3MST (over varied shuttle distances), with the 3MST estimating a lower CV compared to the 3MRT [19–21]. This is explained by multiple mechanical variables and physiological differences between linear and shuttle run tests [20]. Although, similar VO_2 kinetics are exhibited between linear and shuttle run tests, which is unexpected given the energetic cost associated with change of direction exercise. This suggests that performance parameters are interchangeable between test formats depending on desired task specificity [20].

Similar VO_2 kinetics between linear and shuttle run tests may conversely be regarded as evidence that, despite the inclusion of shuttles, the 3MST does not adequately represent the task specific intermittent nature of team-sports. The 7MST has been developed and validated to address this gap [22]. The 7MST is a 7-minute field test, that consists of three rounds of repeated all-out shuttle sprints, interspersed with decremental rest periods and is proposed to offer a reliable and more ecologically valid alternative for assessing CV in team-sport contexts [22]. The lack of explicit 3MRT, 3MST and 7MST comparison within literature has deemed the task specific derivation of CV between linear and shuttle run tests across continuous and intermittent methods inconclusive.

Therefore, the purpose of the study was to provide a novel comparison of the 3MST, 7MST and 3MRT for the CV modelling of team-sport athletes and assess the test-retest reliability. We tested the hypothesis that CV and maximal speed will differ between linear and shuttle run tests, thus CV and maximal speed are task specific. We also tested the hypothesis that the 3MST and 7MST provide reliable measures of CV and thus shuttle tests offer a task specific and accurate alternative for measuring CV in team-sport athletes.

METHODS AND MATERIALS

Experimental Approach to the Problem

A repeated measures experimental design was adopted to assess task specificity of the CV concept. The dependent variables of the study were CV and maximal speed, whereas the independent variable was test mode (i.e., 3MRT, 3MST and 7MST). The reliability of shuttle test modes (i.e., 3MST and 7MST) were assessed across respective trials.

Subjects

A priori power analysis was conducted using G*Power software (Version 3.1), which estimated a minimum sample size of 9 for an effect size of 0.5, alpha level of 5% and statistical significance and power of 95% (p < 0.05). All values are reported as means ± SD unless otherwise stated. Statistical analyses were conducted using Statistical Package for Social Sciences software (SPSS; Version 22).

Twelve semi-professional trained footballers (age: 23 ± 4 years; body mass: 75.94 ± 10.05 kg; stature: 177.42 ± 6.73 cm) were systematically sampled and voluntarily completed the study. One participant was excluded after sustaining injury, meaning a total of 11 participants (age: 23 ± 4 years; body mass: 75.57 ± 10.45 kg; stature: 178.05 ± 6.68 cm) completed the study. Prior institutional ethics committee approval was granted (SMUETHICS202223210), followed by written informed consent from the cohort. Those free of musculoskeletal injury in the previous 6-months and cardiovascular contraindications, as verified from completion of a Physical Activity Readiness Questionnaire (PAR-Q), were included for selection.

Procedures

Participants attended 10 visits, comprising of 3 familiarisation sessions, followed by 7 testing sessions, in a randomised order (Research Randomizer), that consisted of 3 trials for each of the 3MST and 7MST protocols and 1 trial of the 3MRT protocol. The 3MST and 7MST took place on a familiar 3rd Generation artificial pitch, whereas the 3MRT took place on a 400m athletics track. Participants were encouraged to maintain normal activity throughout the study but were asked to ensure a minimum of 24-48 hours recovery before and after each testing visit, with between-testing session duration not exceeding 72 hours. Participants were also instructed to abstain from alcohol consumption during the 24-48-hour recovery periods, abstain from caffeine and food consumption 2-3 hours prior to testing and arrive in a hydrated state.

Critical Velocity Performance Tests

Prior to testing all participants were fitted with a FieldWiz 2nd generation 10Hz GPS unit and integrated heart rate (HR) vest (Advanced Sports Instruments, Lausanne, Switzerland). A 5-minute warm-up, consisting of a 2-minute jog and lower body dynamic stretching exercises followed and was led by the investigator. A recovery period was then provided, the time of which depended on the participant's HR returning to <100 beats per minute (BPM). This aimed to prevent CV being exceeded and to provide restitution for any depletion of *D´* (28). The participants then completed the designated testing session.

Familiarisation Trials:

Participants collectively took part in 3 familiarisation sessions, where 1 trial of each of the 3 test modes (3MRT, 3MST, and 7MST) was performed on each familiarisation visit. Participant stature (213 Portable Stadiometer, SECA GmbH & Co., Hamburg, Germany) and body mass (Portable Scale BC-730, Tanita Corporation of America, Inc., IL, USA) was recorded during initial familiarisation sessions. The methods for each test mode were as follows.

3MRT:

The 3MRT was conducted on a 400m athletics track. Participants began at the start of the 100m line on the inside lane and were instructed to maximally sprint and maintain as fast of a running speed as possible around the track for the 3-minute duration. A blown whistle signalled the start of the test, at which point a stopwatch was started. The test was stopped at 3-minutes and 10-seconds to allow for a full GPS recording [8].

3MST:

Figure 1 depicts the layout of the 3MST. Cones were set up at a distance of 30m apart with a 5m wide zone to constrain participants to a linear running path. Participants began at the start line and were instructed to run the continuous 30m switchbacks as fast as possible for the 3-minute duration. A blown whistle signalled the start of the test, at which time a stopwatch was started. The test was stopped at 3-minutes and 10-seconds to allow for a full GPS recording [18].

7MST:

Figure 1 depicts the layout of the 7MST. Cones were set up at a distance of 18.3m apart with a 5m wide zone to constrain participants to a linear running path. Participants began at the start line and were instructed to run each 18.3m switchback maximally. A blown whistle signalled the start, at which time a stopwatch was started to monitor the 7-minute duration. The 7-minute test was segmented into 3 rounds that immediately followed each other. On return to the start line from each switchback sprint effort, participants were afforded a rest interval that corresponded to the round. This was monitored using the stopwatch lap function with restart signalled by a blown whistle. Round 1 lasted 3-minutes and allowed 15-seconds recovery after each sprint effort. Round 2 lasted 2-minutes and allowed 10-seconds recovery after each sprint effort. Round 3 lasted 2-minutes and had no rest intervals as it was a continuous sprint effort [22]. The test was stopped at 7-minutes and 10-seconds to allow for a full GPS recording.

For each of the three test modes participants were given strong verbal encouragement throughout but, neither time elapsed nor remaining was disclosed to prevent pacing. Pacing for each trial was assessed post-test and identified via graphical characteristics non-representative of the expected hyperbolic relationship. Discrepant trials were subsequently omitted, and repeated following recovery procedures outlined [8,18,22].

*** Insert Figure 1 near here ***

DATA AND STATISTICAL ANALYSIS

GPS was used to monitor speed and time metrics, with HR recorded via the integrated HR monitor within the GPS vest. Extraction of this raw data to Microsoft Excel (2007 Edition) enabled retrospective frame-by-frame analysis and computation of trials to calculate CV and record maximal speed and HR. For the 3MRT and 3MST modes, CV was calculated as an average velocity from the final 30-seconds of the test [8]. Whereas for the 7MST mode, CV was calculated as the average velocity of the final four sprints from the third round of the test [22]. This method is similar to the retrospective video-motion analyses utilised in both the 3MST and 7MST studies but differs through the use of GPS. Despite conflicting reports of GPS validity and reliability within shuttle running and team-sports movement demands [23,24], the use of GPS was rationalised for the present study as the 10 H_z GPS units provide sufficient accuracy and intra-reliability compared to video-motion analyses [25]. The present study refrained from analysing and comparing finite metabolism (*D´*) between test modes. This is due to its omission by the original authors of the 7MST, based on strong evidence that non-linear and high individual variability exists within the reconstitution of *D´*, which prohibits an accurate calculation within intermittent tasks [22].

Comparison between CV Test Modes

A Shapiro-Wilks test was conducted to assess if the data were normally distributed. Only the first trial of both the 3MST and 7MST along with the one 3MRT trial were used for statistical analysis. Main effects for differences in CV and maximal speed ($km.h^{-1}$) between the CV test modes was analysed via a one-way repeated-measures analyses of variance (ANOVA). Partial eta^2 ($\eta_p{}^2$) was reported to assess the magnitude of any significant p value, with values of 0.01, 0.06 and 0.14 representing small, medium and large effect sizes, respectively [26]. *Post hoc* analysis with Bonferroni correction were used to assess where significant differences occurred between CV test modes for CV and maximal speed. Percentage difference for each interaction was manually calculated and reported along with the mean difference and 95% confidence intervals (CI).

Test-Retest Reliability and Interaction between CV Shuttle Tests Trials

A two-way repeated measures ANOVA was performed to assess main effects and interactions between the two CV shuttle tests and their respective trials. Test-retest reliability for CV estimated from each of the 3MST and 7MST trials was assessed via intra-class correlation coefficient (ICC) analysis (two-way random model with absolute agreement) with a confidence interval of 95% to signify excellent reliability [27]. Conservative values of less than 0.5, between 0.5 – 0.75, between 0.75 – 0.9 and greater than 0.9 were used to interpret poor, moderate, good and excellent reliability, respectively [27]. Systematic bias of the two CV shuttle tests was analysed by calculating the grouped coefficient of variation (CoV) across respective trials. Agreement between trials for the 3MST and 7MST modes was also assessed using Bland-Altman analysis and reporting mean bias and 95% limits of agreement (LoA).

RESULTS

Comparison between CV Test Modes

One participant's representative data for the 3MRT, 3MST and 7MST are illustrated in Figure 2, showing the different characteristics of each CV test mode and demonstrating the hyperbolic relationship within each test mode that is indicative of the CV concept. These differences are reinforced by the significant within-subjects main effects observed between CV test modes for both CV ($F_{(2,20)} = 50.96$, $\eta_p^2 = 0.84$, $p < 0.001$) and maximal speed ($F_{(2,20)} = 79.94$, $\eta_p^2 = 0.89$, $p < 0.001$).

*** Insert Figure 2 near here ***

Table 1 summarises *post hoc* pairwise analysis, highlighting where significant differences occurred between the three CV test modes for CV and maximal speed (km.h^{-1}). The following results are reported as mean bias, 95% CI, p value to explain differences and effect size among tests. The 3MST (4.05 km.h^{-1}, 95% CI = 2.61 – 5.49 km.h^{-1}, $p < 0.001$) and 7MST (5.14 km.h^{-1}, 95% CI = 3.34 – 6.94 km.h^{-1}, $p < 0.001$) obtain significantly slower CV, compared to the 3MRT, respectively. The difference in CV derived from the 3MST and 7MST compared to the

3MRT was 28.37% and 36.06% slower, respectively. Similarly, the 3MST (2.88 km.h^{-1}, 95% CI = 1.29 – 4.48 km.h^{-1}, $p < 0.01$) and the 7MST (5.93 km.h^{-1}, 95% CI = 4.44 – 7.41 km.h^{-1}, $p < 0.001$) obtained significantly slower maximal speeds, compared to the 3MRT, respectively. The difference in maximal speed derived from the 3MST and 7MST was 9.94% and 20.40% slower respectively, compared to the 3MRT. Minimal difference was viewed between the 3MST and 7MST (1.09 km.h^{-1}, 95% CI = $^{-}$0.25 – 2.43 km.h^{-1}, $p = 0.13$) for CV, representing the 3MST to be marginally faster (10.77%). However, a significantly faster maximal speed was achieved in the 3MST compared to the 7MST (3.04 km.h^{-1}, 95% CI = 2.21 – 3.87 km.h^{-1}, $p < 0.001$) representing the 3MST to be 11.61% faster.

*** Insert Table 1 near here ***

Test-Retest Reliability and Interaction between CV Shuttle Tests Trials

Despite, both shuttle tests exhibiting poor reliability (ICC < 0.5), ICC analysis suggests that CV from the 3MST (ICC = 0.37, 95% CI: 0.03 – 0.73) offers a greater test-retest reliability compared to the 7MST (ICC = 0.05, 95% CI: -0.23 – 0.49). Additionally, CoV analysis identifies that the 3MST (CoV = 7.57%) offers lower systematic bias compared to the 7MST (CoV = 11.56%). There was a significant main effect between shuttle test modes (3MST and 7MST) ($F_{(1,10)} = 7.33$, $\eta_p^2 = 0.42$, $p = 0.02$) but not between trials ($F_{(2,20)} = 3.00$, $\eta_p^2 = 0.23$, $p = 0.72$), as supported by no significant CV mean biases exhibited across all trials (see Table 1). Nor was there any significant interaction between shuttle test mode and trial ($F_{(2,20)} = 0.17$, $\eta_p^2 = 0.02$, $p = 0.84$).

DISCUSSION

This study demonstrated that novel shuttle tests (3MST and 7MST) derive slower CV compared to linear run test formats (3MRT). This study also demonstrated that the 3MRT attained fastest maximal running speeds, followed by the 3MST and 7MST, respectively. This surprisingly coincided with minimal difference in CV between the 3MST and 7MST, which may pose the inclusion of rest intervals redundant in shuttle test formats. Finally, the 3MST appears to be a marginally more reliable test method compared to the 7MST (ICC Δ = 0.32).

Both the 3MST and 7MST modes respectively derived CV values that were approximately 32% and 39% slower compared to the 3MRT method. This is consistent with previous literature suggesting CV is less tolerant during intermittent compared to continuous cycling and running exercise modes [13,28]. This trend is also demonstrated by differences between the linear (3MRT) and shuttle (3MST) run tests, with lower CV estimation exacerbated over shorter shuttle distances [21]. This could be attributed to the greater quantity of changes of direction performed with shorter shuttle distances and subsequent increased neuromuscular fatigue and intramuscular metabolic demand [3,16,29]. This infers practical ramifications on the specific application of the CV concept for fatigue monitoring and training prescription of intermittent and team-sport athletes. For example, faster CV's estimated from linear methods would result in misjudged finite energy balance (D'_{bal}) and training intensity calculation if applied to intermittent specific tasks [14]. More recently, these differences in CV estimation have been attributed to differences of peak energetic parameters between linear and shuttle tests that coincides with minimal differences observed across average measures, suggesting the application of linear and shuttle CV tests within team-sport athletes are likely interchangeable [20]. Therefore, maximal speed achieved is likely an overlooked and important task specific variable that must be considered when selecting a CV test modality.

Our results indicate both the 3MST and 7MST allow for slower maximal speeds to be attained (approximately 10% and 20%, respectively) compared to the 3MRT. The 3MST allows for a (approximately 12%) faster maximal speed compared to the 7MST, confirming that task specificity of maximal speed explicitly exists between CV shuttle test modes, supporting a positive correlation between running speed and shuttle distance that explains CV sensitivity to shuttle distance [19,21]. It is however plausible, that Kramer and colleague's use of slow sampling 1H_z GPS and analysis software that filtered high-speed (100H_z) video to 1-3 H_z, may be limited by unreliability and exacerbated through measuring high speed change of direction and shuttle running [24]. In contrast, we adopted higher rate 10H_z GPS, which has good reliability and accuracy in measuring team-sport movement demands [25,30]. Therefore, the present study offers updated evidence supporting that maximal speed is an important task specific variable within the CV model and should be considered when selecting a shuttle test modality for modelling CV in intermittent and team-sport athletes. This is because varied pitch dimensions, tactics and rulings amongst team-sports, restrict high-speed running to sport-specific, relative speed zones [31–34] that are more representative of acceleration as opposed to an athlete's top-end velocity. Furthermore, variable high-speed running profiles exhibited across playing positions within the same sport [33,34], gives credence to the individualisation of CV shuttle test selection to ensure positional demands are mimicked. For example, a practitioner may select a shorter distance

CV shuttle test to assess a central midfield player who performs a high frequency of changes of direction and slower maximal speeds in match play over a reduced pitch area. Alternatively, a longer distance CV shuttle test might be selected to assess a wing-back player who achieves faster maximal speeds in match play over greater pitch area.

Currently the CV concept, via the 3MRT, is applied to HIIT prescription in team-sport configurations by standardising rest intervals [11]. Although this application is limited as it results in athletes encountering varied work:rest ratios. Additionally, the calculation of standardised work:rest intervals is dependent on the prerequisite estimation of *D´*, which is notoriously inaccurately modelled in intermittent exercise [14,15,35]. Contemporary energetics models have improved reliability and accuracy in linear and intermittent running but continue to overestimate *D´* [36], highlighting the need for further clarity. Despite this, the velocity-time relationship can be manipulated in HIIT prescription to achieve specific training adaptations. For example, intervals performed slightly excessive of CV for 90-300-second durations will increase CV at the expense of *D´*. Whereas intervals of less than 90-seconds allow for greater supramaximal intensities of CV and result in small CV adaptations whilst preserving *D´* [11]. This mechanism is of specific interest to team-sport athletes, who aim to concurrently improve endurance capacity without compromising sprinting capacity. Future research must firstly provide accurate modelling of *D´* in intermittent exercise and secondly, specify the intensities of CV required for such specific training adaptations. In doing so, these speculative benefits to sport and position specific applications of the CV model within HIIT prescription and fatigue monitoring of team-sport athletes can be confirmed.

Our results demonstrate minimal difference in CV between the 3MST and 7MST. This is surprising as a lower CV would have been expected via the 7MST, given that it is run over a shorter shuttle distance compared to the 3MST [19,21]. Rather, agreement in CV between the 3MST and 7MST, across all trials, suggests that no such shuttle distance CV sensitivity is exhibited between the 3MST and 7MST. This is most likely explained by the intermittent nature of the 7MST compared to the continuous 3MST, whereby the rest intervals afforded in the 7MST likely provide sufficient metabolic restitution of *D´* that allows for greater CV tolerance [37]. This alludes that rest intervals are potentially an additional task specific variable to consider in CV shuttle test selection. Additional research should therefore explore physiological and mechanical comparisons between the 3MST and 7MST to confirm the potential task specificity of rest intervals.

Future research is also required to provide clarity and an accurate model of finite capacity within intermittent exercise before specified rest intervals can be included in shuttle test formats. As currently, the expected shuttle distance CV sensitivity between the 3MST and 7MST is unobserved. This poses that the structured rounds of depreciating rest intervals included in the 7MST distort CV estimation and are likely redundant when applied in combination with shuttle methods that exhibit changes of direction. Thus, the CV concept appears to accept modification to shuttle distances, as evidently applied with the 3MST [19,21], whereby the maximal speeds run within CV shuttle tests are consequentially regulated. This offers the flexibility to design CV tests with task specific shuttle distances, which, postulates preference of the 3MST as a mode that can be reliably modified to fulfil intermittent and team-sport task specificity.

The present study indicates that the 3MST offers greater reliability (ICC = 0.32) and less variance (3.99%) compared to the 7MST. Based on anecdotal evidence and consistency of all other variables, this is likely the result of the 7MST's timed rounds, which makes blinding athletes to time remaining difficult and allows for the possibility of subtle pacing. This may exacerbate unreliability of the 7MST when combined with the non-linear and highly individualised reconstitution of finite metabolism documented within intermittent exercise [14]. Similarly, the 3MST consistently calculates CV as an average of the last 30 seconds, a constant timepoint. Whereas the 7MST estimates CV as the average speed of the last 4 sprints, which despite previous validation [22], allows for intra-rater reliability to be questioned. Whilst this provides further preliminary preference of the 3MST mode, caution should be heeded as both shuttle test modes appear to have poor test-retest reliability; ICC < 0.5 [27]. It is conceivable that the poor reliability observed in both shuttle tests via ICC analysis is misrepresented by the present study's small sample size and possibly further compounded by small variability [38]. This is exemplified by a lack of any main effect or interaction between the shuttle tests and trials. Additionally, the non-signifcant mean biases and good agreement reported across trials, infers good test-retest reliability for both the 3MST and 7MST. This strongly indicates, that unlike the 3MRT, no learning or training-induced effects exist within the 3MST and 7MST modalities [21], contradicting the low ICC values we reported. Such contradiction is frequently reported with

ICC reliability analysis, predominantly due to its vulnerability to minimal sample variability, which limits the efficacy of ICC reliability analysis to obtain conclusive results [39]. This suggests that ICC should not be the sole measure employed to assess test-retest reliability. Thus directing future research to recruit a larger, strongly defined and fixed sample population to conclusively assess test-retest reliability of the 3MST and 7MST.

CONCLUSION

Our study confirms that differences exist between linear and shuttle test methods for the modelling of CV within a cohort of football players. Therefore, the change of direction associated with novel shuttle test methods offer a task specific format that seminal research has identified, accurately modeling CV for intermittent and team-sport performance. Novel CV shuttle tests are therefore advocated for application with intermittent and team-sport athletes as an alternative or adjunct to linear test modes. However, the maximal speed run in shuttle test modes is an additional task specific variable that must be considered when selecting a shuttle test, as varied high-speed demands among team-sports and playing positions may predicate practitioner’s choice of test to ensure optimisation of specific and individualised HIIT and fatigue monitoring. Despite inconclusive test-retest reliability, the unexpected CV relationship associated with the 7MST could suggest that rest intervals are likely redundant in a CV shuttle test format. Instead, shuttle distance could be considered to be a modifiable variable that practitioners utilise to regulate maximal speed and further increase the task specificity of CV shuttle tests.

SUMMARY BOX

Our findings suggest that shuttle tests derive significantly slower CV and maximal speeds compared to linear tests, and thus likely provide greater task specificity for CV modelling of team-sport athletes. The good agreement between trials for shuttle tests warrants further investigation.

ACKNOWLEDGEMENTS

The authors would like to thank the football club for permitting access to its playing staff and particular appreciation to the players who participated in the study. Gratitude is also extended to Advanced Sports Instruments for the technical support given to rectify early software issues.

No conflicts of interest are declared. This includes no funding mechanisms, personal or professional relationships existing with any beneficiaries of the findings in the present study. The results of the study are presented honestly and without fabrication, falsification or inappropriate data manipulation. The present study does not constitute endorsement by NSCA.

DECLARATIONS

Funding

No funding was provided for the present study.

Conflicts of Interest

No conflicts of interest are declared. This includes any personal or professional relationships existing with any beneficiaries of the findings of the present study.

Availability of Data

All data is transparent, confidentially stored and available upon request.

Authors' Contributions

S. E. A. contributed to the experimental conception and design, collection, analysis and interpretation of data and writing of this article. S. L. C., and S. D. P., contributed to the experimental conception and design, data interpretation, critical review and editing of this article.

Ethics Approval

Prior institutional ethics was granted via St Mary's University ethics committee.

Consent for Participation

Informed written consent was obtained from all participants and the chairman of Balham Football Club, from whom partcipants were recruited.

Consent for Publication

Not applicable.

REFERENCES

1. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the English Premier League. *Int J Sports Med*. 2014;35(13):1095-1100.

2. Bradley PS, Ade JD. Are current physical match performance metrics in elite soccer fit for purpose or Is the adoption of an integrated approach needed? *International Journal of Sports Physiology & Performance*. 2018;13(5):656-664.

3. Dellal A, Keller D, Carling C, Chaouachi A, Wong DP, Chamari K. Physiologic effects of directional changes in intermittent exercise in soccer players. *Journal of Strength and Conditioning Research*. 2010;24(12):3219-3226.

4. Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B, Goodman C. Time–motion analysis of elite field hockey, with special reference to repeated-sprint activity. *Journal of Sports Sciences*. 2004;22(9):843-850. doi:10.1080/02640410410001716715

5. Bangsbo J, Mohr M, Krustrup P. Physical and metabolic demands of training and match-play in the elite football player. *Journal of Sports Sciences*. 2006;24(7):665-674.

6. Waldron M, Highton J. Fatigue and pacing in high-intensity intermittent team sport: An update. *Sports Med*. 2014;44(12):1645-1658. doi:10.1007/s40279-014-0230-6

7. Rampinini E, Bishop D, Marcora SM, Bravo DF, Sassi R, Impellizzeri FM. Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *Int J Sports Med*. 2007;28(03):228-235.

8. Pettitt RW, Jamnick N, Clark IE. 3-min all-out exercise test for running. *Int J Sports Med*. 2012;33(6):426-431.

9. di Prampero PE. The concept of critical velocity: a brief analysis. *Eur J Appl Physiol*. 1999;80(2):162-164.

10. Smith CG, Jones AM. The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. *Eur J Appl Physiol*. 2001;85(1-2):19-26.

11. Pettitt RW. Applying the critical speed concept to racing strategy and interval training prescription. *International Journal of Sports Physiology & Performance*. 2016;11(7):842-847.

12. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle. *Sports Med*. 2013;43(5):313-338.

13. Morton RH, Billat LV. The critical power model for intermittent exercise. *Eur J Appl Physiol*. 2004;91(2-3):303-307.

14. Jones AM, Vanhatalo A. The ‘critical power’ concept: Applications to sports performance with a focus on intermittent high-intensity exercise. *Sports Med*. 2017;47(1):65-78.

15. Skiba PF, Clarke D, Vanhatalo A, Jones AM. Validation of a novel intermittent w’ model for cycling using field data. *Int J Sports Physiol Perform*. 2014;9(6):900-904.

16. Hatamoto Y, Yamada Y, Sagayama H, Higaki Y, Kiyonaga A, Tanaka H. The relationship between running velocity and the energy cost of turning during running. *PLoS ONE*. 2014;9(1):1-8.

17. Stevens TGA, De Ruiter CJ, Van Maurik D, Van Lierop CJW, Savelsbergh GJP, Beek PJ. Measured and estimated energy cost of constant and shuttle running in soccer players. *Med Sci Sports Exerc*. 2015;47(6):1219-1224. doi:10.1249/MSS.0000000000000515

18. Saari A, Dicks ND, Hartman ME, Pettitt RW. Validation of the 3-minute all-out exercise test for shuttle running prescription. *Journal of Strength and Conditioning Research*. 2019;33(6):1678-1684.

19. Kramer M, Du Randt R, Watson M, Pettitt RW. Oxygen uptake kinetics and speed-time correlates of modified 3-minute all-out shuttle running in soccer players. *PLoS ONE*. 2018;13(8):1-15.

20. Kramer M, Du Randt R, Watson M, Pettitt RW. Energetics of male field-sport athletes during the 3-min all-out test for linear and shuttle-based running. *Eur J Appl Physiol*. 2019;119(2):477-486. doi:10.1007/s00421-018-4047-0

21. Kramer M, Watson M, Du Randt R, Pettitt RW. Critical speed as a measure of aerobic fitness for male rugby union players. *International Journal of Sports Physiology & Performance*. 2019;14(4):518-524.

22. Kirby BS, Bradley EM, Wilkins BW. Critical velocity during intermittent running with changes of direction. *Medicine & Science in Sports & Exercise*. 2019;51(2):308-314.

23. Beato M, Bartolini D, Ghia G, Zamparo P. Accuracy of a 10 Hz GPS Unit in measuring shuttle velocity performed at different speeds and distances (5 - 20 M). *Journal of Human Kinetics*. 2016;54(1):15-22.

24. Varley MC, Fairweather IH, Aughey RJ. Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences*. 2012;30(2):121-127.

25. Rampinini E, Alberti G, Fiorenza M, et al. Accuracy of GPS devices for measuring high-intensity running in field-based team sports. *Int J Sports Med*. 2015;36(01):49-53. doi:10.1055/s-0034-1385866

26. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Academic Press; 2013.

27. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*. 2016;15(2):155-163.

28. Chidnok W, Dimenna FJ, Bailey SJ, et al. Exercise tolerance in intermittent cycling: Application of the critical power concept. *Medicine & Science in Sports & Exercise*. 2012;44(5):966-976. doi:10.1249/MSS.0b013e31823ea28a

29. Buchheit M, Bishop D, Haydar B, Nakamura FY, Ahmaidi S. Physiological responses to shuttle repeated-sprint running. *Int J Sports Med*. 2010;31(6):402-409. doi:10.1055/s-0030-1249620

30. Johnston RJ, Watsford ML, Kelly SJ, Pine MJ, Spurrs RW. Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. *Journal of Strength and Conditioning Research*. 2014;28(6):1649-1655.

31. Gabbett TJ. Use of relative speed zones increases the high-speed running performed in team sport match play. *Journal of Strength and Conditioning Research*. 2015;29(12):3353-3359. doi:10.1519/JSC.0000000000001016

32. Young WB, Duthie GM, James LP, Talpey SW, Benton DT, Kilfoyle A. Gradual vs. maximal acceleration: Their influence on the prescription of maximal speed sprinting in team sport athletes. *Sports*. 2018;6(3):66. doi:10.3390/sports6030066

33. Carling C, Bradley P, McCall A, Dupont G. Match-to-match variability in high-speed running activity in a professional soccer team. *Journal of Sports Sciences*. 2016;34(24):2215-2223. doi:10.1080/02640414.2016.1176228

34. Bush MD, Archer DT, Hogg R, Bradley PS. Factors influencing physical and technical variability in the English Premier League. *International Journal of Sports Physiology & Performance*. 2015;10(7):865-872.

35. Skiba PF, Chidnok W, Vanhatalo A, Jones AM. Modeling the expenditure and reconstitution of work capacity above critical power. *Medicine & Science in Sports & Exercise*. 2012;44(8):1526-1532.

36. Vassallo C, Gray A, Cummins C, Murphy A, Waldron M. Exercise tolerance during flat over-ground intermittent running: Modelling the expenditure and reconstitution kinetics of work done above critical power. *Eur J Appl Physiol*. 2020;120(1):219-230. doi:10.1007/s00421-019-04266-8

37. Chidnok W, DiMenna FJ, Fulford J, et al. Muscle metabolic responses during high-intensity intermittent exercise measured by 31P-MRS: Relationship to the critical power concept. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*. 2013;305(9):1085-1092. doi:10.1152/ajpregu.00406.2013

38. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*. 2005;19(1):231. doi:10.1519/15184.1

39. Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med*. 1998;26(4):217-238. doi:10.2165/00007256-199826040-00002

TABLES AND FIGURES

Table 1. Mean ± SD Critical Velocity (CV) and Maximal Speed for the 3-Minute All-Out Running Test (3MRT), 3-Minute All-Out Shuttle Test (3MST) and 7-Minute Intermittent Shuttle Test (7MST), first trials only. Alongside across trials Bland-Altman analysis reporting CV mean bias ± SD and 95% Limits of Agreement (LoA) for the 3MST and 7MST.

	CV (km.h^{-1})	Maximal Speed (km.h^{-1})	Trial Comparison	CV Mean Bias (km.h^{-1})	95% LoA
3MST	10.12 ± 0.97 $^{c+}$	26.18 ± 1.71 $^{b+, c*}$	T^1 v T^2	-0.67 ± 1.39	-3.40 – 2.06
			T^1 v T^3	-0.71 ± 0.95	-2.58 – 1.14
			T^2 v T^3	-0.05 ± 1.22	-2.45 – 2.35
7MST	9.03 ± 0.97 $^{c+}$	23.14 ± 1.10 $^{a+, c+}$	T^1 v T^2	-0.80 ± 1.82	-4.24 – 2.64
			T^1 v T^3	-0.48 ±1.82	-3.87 – 2.92
			T^2 v T^3	1.00 ± 1.82	-3.10 – 3.75
3MRT	14.17 ± 1.49 $^{a+}$, $^{b+}$	29.07 ± 2.19 ^{a*}, $^{b+}$	-	-	-

Abbreviations: ^{a} = Statistically different to the 3MST; ^{b} = Statistically different to the 7MST; ^{c} = Statistically different to the 3MRT; * = $p <$ 0.01; + = $p < 0.001$; T^1 = Trial 1; T^2 = Trial 2; T^3 = Trial 3 (for respective test modes).

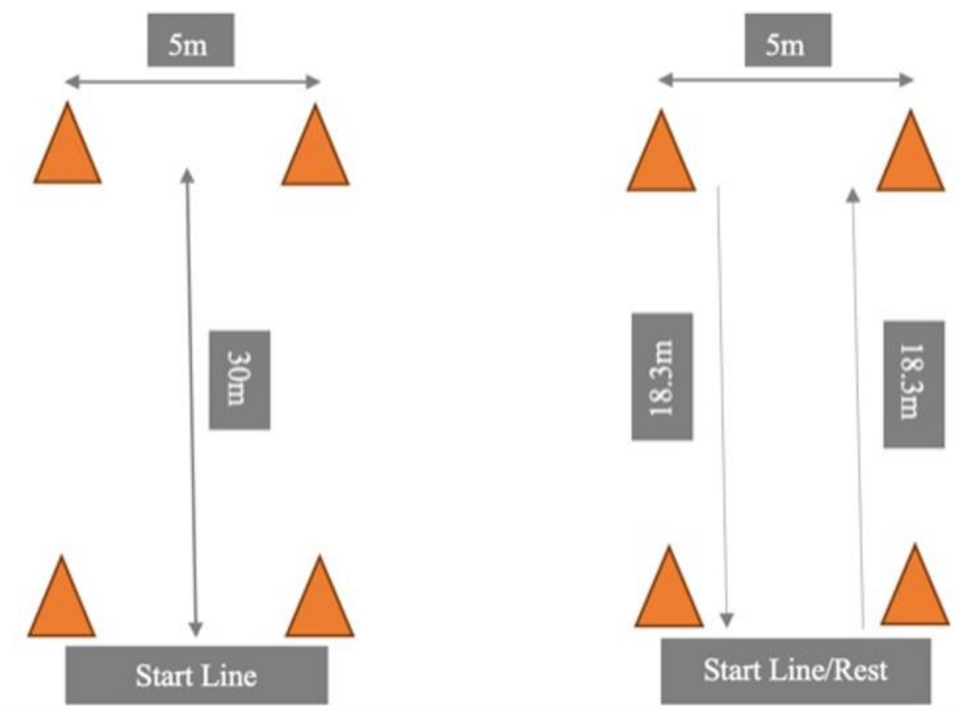

Figure 1. Example of the field setup for the 3-Minute All-Out Shuttle Test (3MST; left) and 7-Minute Intermittent Shuttle Test (7MST; right).

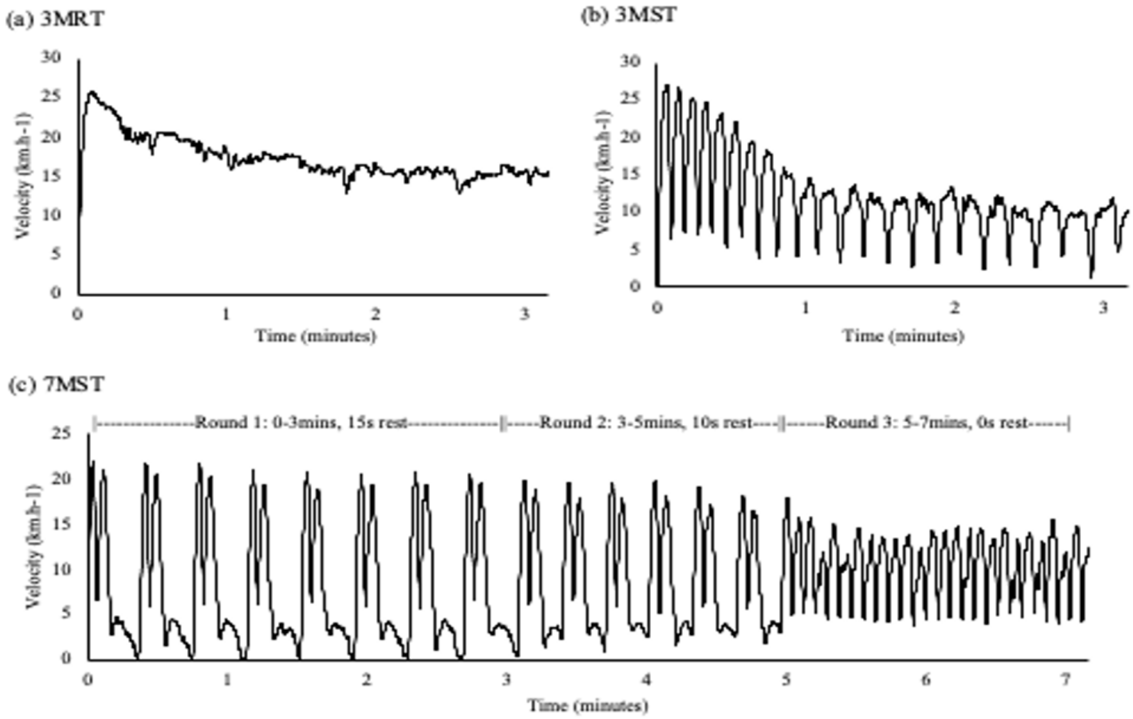

Figure 2. Graphical representation of the varied velocity/time profiles between the **(a)** 3-Minute All-Out Running Test (3MRT), **(b)** 3-Minute All-Out Shuttle Test (3MST) and **(c)** 7-Minute Intermittent Shuttle Test (7MST) for a representative participant. Particular attention should focus on the peak, representing maximal speed and hyperbola, representing critical velocity, which best demonstrate key characteristic differences of each test. In addition, it should be noted that the 7MST clearly exhibits a far more intermittent profile compared to the 3MST.