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Abstract

Objectives: To evaluate the criterion and longitudinal validity of field- and laboratory-derived heart rate (HR) indices of resting and submaximal fitness tests (SMFTs) as measures of cardiorespiratory fitness.

Design: Observational, repeated measures.

Methods: Twenty-nine semi-professional footballers participated. Laboratory assessments took place at the start and end of a preseason training period, whereby resting, SMFT HR-derived indices, and criterion measures of cardiorespiratory fitness (running economy [RE], maximal oxygen uptake [$\dot{V}O_2$ max] and aerobic speed [MAS]) were collected. Throughout this training period, two field-based SMFT protocols, prescribed at different intensities, were administered weekly. Individual slopes were calculated from the analysis of within-athlete change scores. Associations between laboratory and field measures were assessed via Pearson's correlation coefficient (*r*) and linear regression models.

Results: Relationships between SMFT HR-derived indices from laboratory and field were very-large for exercise HR (*r*=0.74 to 0.87) and moderate to very-large for HR recovery (0.43 to 0.76). Moderate to very-large inverse relationships were observed between exercise HR and HR recovery with $\dot{V}O_2$ max and MAS (–0.41 to –0.78), whereas resting HR showed no substantial relationships. Changes in exercise HR showed large and very-large inverse correlations with preseason changes in $\dot{V}O_2$ max (–0.54 to –0.60) and MAS (–0.64 to –0.83). Relationships between changes in HR recovery and maximal cardiorespiratory criterion measures were moderate to large (–0.32 to –0.63).

Conclusion: SMFT exercise HR is a valid proxy measure of cardiorespiratory fitness irrespective of test setting, whereas the validity of HRR remains elusive and appears to vary between exercise intensities.

Keywords: Submaximal Fitness Tests, Team sports, Monitoring, Testing, Exercise heart rate, Heart rate recovery

Introduction

Cardiorespiratory fitness is a fundamental component of football (soccer), enabling players to sustain the physical demands of the sport, including high-intensity intermittent efforts, explosive directional and velocity changes, and maximal sprints[1]. It has also been identified as a modifiable factor in enhancing recovery time-course[2] and mitigating the risk of muscle injury[3]. Understanding cardiorespiratory fitness is therefore important in high-performance football. Criterion assessments of cardiorespiratory fitness are typically performed in controlled laboratory settings and involve incremental tests to exhaustion[4], allowing for quantification of maximal physiological and physical capacities (e.g., maximal oxygen uptake [$\dot{V}O_2$ max] and maximal aerobic speed [MAS])[4,5]. However, such assessments have pragmatic challenges (e.g., time consuming, exhaustive, resource intensive), and therefore cannot be conducted routinely within professional teams[6].

Submaximal fitness tests (SMFTs) allow practitioners to reliably, and frequently assess athlete's physiological state[6], primarily via heart rate (HR) derived indices (e.g., exercise HR [HRex] and HR recovery [HRR])[6]. These measures have also shown moderate to very-large associations with cardiorespiratory fitness across a range of team-sport athletes[7], ultimately delivering a pragmatic assessment tool. The advantages of SMFTs stem from their non-exhaustive nature, and the ease which they can be administered to a large group of athletes simultaneously in field settings as a discrete (albeit standardised) component of training (e.g., low-intensity running as warm-up, or high-intensity bouts as priming activities)[8]. Inevitably, this means that extraneous factors, including changes in environmental conditions (e.g., temperature, humidity, wind speed, ground hardness), teammate interactions, psycho-emotional factors, and pacing strategies could influence HR responses and subsequent interpretations of longitudinal changes in cardiorespiratory fitness[6,9].

While the usefulness of HR-derived indices monitored during and immediately following SMFTs have been established in the literature, there remain important questions that are yet to be investigated. For instance, studies exploring the utility of SMFT in team sports have been conducted in isolation, either within a laboratory[10] or a field[11] setting. However, at present, there is a dearth of empirical evidence on the concurrent agreement between SMFT HR-derived indices collected as part of on-field football training with those observed in controlled laboratory conditions. Moreover, despite available meta-analytic evidence suggesting a robust convergent validity (i.e., correlation magnitudes) of HRex as an indicator of cardiorespiratory fitness[7], and negligible effects of key programming variables such as exercise intensity, these findings primarily stem from between-athlete comparisons. While such comparisons may be useful when comparing between individuals (i.e., an athlete with a lower HRex might typically be seen to possess a higher cardiorespiratory fitness) at a particular instance, they may not accurately reflect the longitudinal and individualised nature inherent to elite sport training monitoring. In this regard, it is noteworthy to highlight that these studies exclusively adopted intermittent field-based assessments as the reference for maximal cardiorespiratory fitness. Less is known about the validity of HR-derived indices in denoting within-athlete changes in cardiorespiratory fitness over a longitudinal training period, particularly in reference to established laboratory gold standard measures, including $\dot{V}O_2$ max and MAS[7]. Accordingly, the aims of this study were (1) to assess the criterion and longitudinal validity of HR-derived indices as proxy measure of cardiorespiratory fitness, whilst also examining the possible influence of exercise intensity; and (2) to evaluate the relationships between SMFT HR-derived indices in controlled laboratory and field conditions in football players.

Methods

Twenty-nine semi-professional male footballers (age: 21.7±3.6 years; body mass: 74.4±7.7 kg; MAS: 19.1±1.6 km·h^{-1}; $\dot{V}O_2$ max: 56.0±5.8 mL·kg·min^{-1}) were recruited from one club competing in the Australian National Premier League (classified as Tier 2 participants[12]). Informed consent and institutional ethics approval were obtained prior the commencement of the study (HREC number: H14606).

Players attended the laboratory 3 to 6 days before (n=19) or within the first 2 weeks (n=10) of preseason (pre-test) and following 6 to 8 weeks (48±3 days [range: 42 to 54]) of preseason (post-test). Within this period, field SMFTs were administered weekly. The study included two main analysis components: (1) criterion validity, as the association between observed SMFT HR-derived indices and criterion measures of cardiorespiratory fitness. To address the pseudo-replication issues arising from between-athlete comparisons[13], we limited our analysis to a single observation per player. (2) Longitudinal validity, as the association between intra-individual preseason change scores (pre to post Δ) in HR-derived indices and criterion measures of cardiorespiratory fitness. Due to COVID-19 pandemic-related constrains (e.g., illness, isolations) and other logistical challenges (e.g., time between consecutive laboratory and field testing, number of repeated measures), a subset of 14 players met the inclusion criteria for this analysis component. A detailed overview of addressing the inclusion criteria is presented in Table S1 and S2 in the supplementary material 1. Analysis components 1 and 2 also sought to assess the agreement between SMFT protocols from both conditions (laboratory and field).

Testing procedures were under similar environmental conditions (field: 23.4±2.5 ℃ [21 to 27] and 67.6±9.8% humidity [range: 60 to 94]; laboratory: 24.7±0.5 ℃ [24 to 25] and 74.2±4.6% humidity [67 to 82]). These conditions were considered as thermoneutral and were not anticipated to impact players’ thermal state during field SMFTs. Players were advised to maintain their normal diet (food and fluids intake) and refrain from alcohol and caffeine consumption at least 24 and 2 h prior to testing, respectively. Field SMFTs were performed 72 h following matches at similar times (7:00–

8:30PM). Laboratory tests were undertaken between 4:00–9:00PM, adopting nearly similar times (±1.5h) across pre- and post-tests for all participants.

Field SMFTs were administered at the final stage of a standardised training warm-up (5–7 min of running movement, dynamic flexibility, and striding) and consisted of two 3 min continuous-fixed bouts across 50 m shuttles[8], prescribed using a custom audio file. Protocols were interceded by 70 s recovery periods. During the initial 60 s, players were instructed to maintain an upright standing position for HRR collection, followed by 10s of interim period before the second SMFT. To explore the effect of SMFT intensity, we elected to target intensities that elicit ~80 and 90% of HR_{max} at baseline for the first and second SMFT, respectively. These particular intensities were chosen because they encompass the intensity ranges most commonly reported in research[7], and could be practically implemented within the team's environment. Based on familiarisation sessions with most players (n=22; 76%), we determined mean running speeds of 11 $km \cdot h^{-1}$ for the first (hereafter, $Field_{80}$) bout and 12.8 $km \cdot h^{-1}$ for the second ($Field_{90}$) bout to elicit the squad-average intended HR responses (supplementary material 2, Fig. S2). Beat-to-beat HR data were collected using the same HR monitors (10 Hz; Polar Team Pro sensor, Kempele, Finland). Subsequently, raw data attained during and immediately following (recovery) the SMFT were exported for analysis.

Upon arrival at the laboratory, players relaxed for 15–20 min before an electrocardiogram HR recording (Powerlab 16/35, ADI Instruments, Sydney, Australia, 1000 Hz) was performed in a quiet room for ~12 min in a supine position. Resting HR (HRrest) and vagal-related HR variability (HRV; using the square root of the mean of the sum of squares of differences between adjacent normal R-R intervals [Ln rMSSD]) were calculated from raw data of the last 3 min of recording[9]. Then, the SMFT was administered as part of an incremental test to exhaustion on a motorised treadmill, following a standardised warm-up procedure akin to that used on-field. Following discussions within the research team, we concluded that administering a single SMFT in the laboratory would be appropriate for several reasons: (1) the time constraints associated with laboratory assessments; (2) preventing excessive fatigue before maximal assessments; and (3) adopting a comparable duration to studies monitoring running economy (RE) in football players, typically 4 min[14]. A visual illustration of the laboratory test protocol is available in Fig. S1 in the supplementary material 2. Briefly, players completed a habitual running stage (1 min at 8 and at 9 km·h^{-1}, and 2 min at 10 km·h^{-1}), followed by a continuous-fixed bout of 4 min at 12 km·h^{-1}. In view of the challenges of matching exercise intensity between the SMFTs in laboratory and field settings (i.e., motorised treadmill versus overground running, change of directions), and ensuring comparability between laboratory to both field SMFT protocols, we attempted to select an intensity that was somewhat in the middle range of the speeds administered on-field, theoretically eliciting an internal response between 80–90% of HR_{max} (supplementary material 2, Fig. S2). Upon completion, players were given 2.5 min of recovery (2 min upright standing, 30 s interim period). Thereafter, the maximal assessment started at 12 km·h^{-1}, increasing by 0.2 km.h^{-1} every 12 seconds until volitional exhaustion[15]. Cardiorespiratory data were collected concurrently using HR monitors (Garmin Premium HR, Garmin Ltd, Kansas, USA) and a metabolic cart (Cosmed Quark, Rome, Italy) using a breath-to-breath measurement mode[16]. Raw data from the manufacture's software were than exported for analysis.

Cardiorespiratory traces (HR, oxygen uptake) from both laboratory and field tests were first visually inspected for data point outliers, detected as lower or greater than 1.5 times the interquartile range from the 1st or 3rd quartile, respectively[8]. HR-derived indices were normalised based on $\%HR_{max}$, quantified as the highest HR recorded during the pre-or-post incremental treadmill tests. HRex was calculated as the average HR during the final 30s of the 3rd min SMFT[7], while HRR was determined as the lowest observed HR value within the last 10s of the 60-s recovery period[8]. Preliminary analyses showed a perfect relationship (r=0.995, mean difference=0.6 % points, standard error of estimate [SEE]=0.6) between SMFT HRex during the 3rd and 4th min, meaning that either is expected to show identical trends. We considered three laboratory outcomes as criterion measures of cardiorespiratory fitness: (1) RE (mean $\dot{V}O_2$ [mL·kg·min^{-1}] during the last 60s of the 4th min SMFT)[14]; (2) $\dot{V}O_2$ max (mL·kg·min^{-1}), representing the peak value recorded from 12 s moving time averaging[15,16]; and (3) MAS, representing the lowest running speed at which $\dot{V}O_2$ max was attained[5].

Statistical analyses were conducted using the R studio environment (version 4.3.1)[17] using the *confintr, lme4, tidyverse, and parameters* packages. A detailed outline of this statistical processes is presented in Table S4 of the supplementary material 1. The relationships between HR-derived indices across testing settings (i.e., laboratory ~ field), and their criterion validity with cardiorespiratory fitness outcomes were examined using Pearson's correlation coefficient (r)[18]. The longitudinal validity of SMFT HR-derived indices was evaluated as: (1) the association between pre–post preseason changes (Δ scores) in SMFT measures and changes in cardiorespiratory fitness outcomes; and (2) by fitting general linear models with a baseline adjustment for obtaining coefficient estimates (intercept and slope), estimates of the coefficient of determination (R^2), and SEE, with 90% compatibility intervals (CI) constructed using a bias corrected accelerated bootstrapping technique of 2000 resamples in replacement of the original data. To mitigate against technical and biological error sources within single (isolated) assessments, changes in HR-derived indices from field SMFTs were calculated from intra-individual repeated measure (weekly) slopes (presented in Fig. S3 and S4 in the supplementary material 2), rather than the pre- and post-tests data points only. To account for the variability in preseason schedules, individuals' predicted estimates were then multiplied by the number of preseason weeks between pre- and post-laboratory assessments (i.e., weekly slope × number of weeks). Correlation magnitudes were scaled against standardised threshold values of 0.10 small; 0.30 moderate; 0.50 large; 0.70 very large; and 0.90 extremely large[19]. Changes in cardiorespiratory fitness criterion measures were evaluated in relation to the 90% CI coverage, relating mostly to the point estimates, and were declared as a positive or negative effect when lower and upper CI did not overlap zero values.

Results

Moderate to very-large correlations were observed between SMFT HR-derived indices in laboratory and field conditions, both for observed values and intra-individual change scores (supplementary material 2, Fig. S5 and 6). SMFT HRex displayed very-large relationships (*r*=0.74 to 0.87), with 90% CI coverage indicating moderate to extremely large magnitudes. In contrast, SMFT HRR relationships ranged from moderate to very-large (r=0.43 to 0.76), with a possibly trivial relationship observed for changes in HRR (Δ % points) in the laboratory with Field_{90} SMFT (r=0.43, 90% CI: –0.03 to 0.74, Fig. S6 in supplementary material 2)

The associations between SMFT HR-derived indices and cardiorespiratory fitness criterion measures are displayed in Fig. 1. Both HRex and HRR showed small to large positive relationships with RE (r=0.27 to 0.58), and moderate to very large inverse relationships with $\dot{V}O_2$ max and MAS (r=–0.41 to –0.78). Compared to the laboratory SMFT, HR-derived indices collected on field showed weaker relationships with RE (moderate), but greater associations with $\dot{V}O_2$ max (90% CI ranged from moderate to very large). Resting HR and HRV measures showed no relationships with any measure of cardiorespiratory fitness (Table S3 in supplementary material 1).

*****Fig 1 around here*****

The relationships between changes in SMFT HR-derived indices and cardiorespiratory fitness criterion measures are displayed in Fig. 2, with models' coefficient estimates, R^2 and SEE for these correlations are presented in Table 1. Trivial relationships were observed between changes in HR-derived indices and RE, except for HRex monitored during the laboratory SMFT (r=0.51 [0.03 to 0.80]). Coefficient estimates indicated trivial effects across all protocols (Table 1). Relationships between changes in HRex and cardiorespiratory fitness were large and very-large for $\dot{V}O_2$ max (r=–0.54 to –0.60) and MAS (r=–0.64 to –0.83), respectively, showing comparable magnitudes across all SMFT protocols (Fig. 2, panel B and C). Coefficient estimates suggested that a reduction in HRex is associated with positive changes in $\dot{V}O_2$ max and MAS (Table 1, panel A). Correlation magnitudes for changes in HRR and cardiorespiratory fitness criterion measures were lower compared to HRex (r=–

0.32 to –0.63, moderate to large; Fig 2, panel E and F), with notable variations observed between laboratory and field settings and across intensities. Slope coefficients were mostly compatible with trivial effects (Table 1, panel B) and the 90% CI width tended to decrease in the Field_{90} protocol, resulting in small, albeit clear moderating effects. The relationships between changes in resting HR and HRV with cardiorespiratory fitness outcomes changes were all trivial or unclear, and therefore coefficient estimates were not further analysed (refer to Table S3 in supplementary material 1).

*****Fig 2 and Table 1 around here*****

Discussion

This study aimed to evaluate the criterion and longitudinal (within-athlete) validity of resting and SMFT HR-derived indices as proxies of training-induced changes in cardiorespiratory fitness, while also accounting for the potential influence of exercise intensity. Considering the evidence to date, it stands out as the first study to concurrently administer SMFTs in both laboratory and field settings and compare their outcome measures to laboratory-derived criterion measures ($\dot{V}O_2$ max, MAS) of cardiorespiratory fitness in football players. The key findings were: (1) the correlations between SMFT HR-derived indices in laboratory and field settings tended to be higher for HRex compared with HRR; (2) HRex and HRR showed moderate to very-large criterion validity with criterion measures of cardiorespiratory fitness; and (3) HRex displayed a higher longitudinal validity to changes in maximal cardiorespiratory fitness measures, irrespective of test setting and exercise intensities. The relationship magnitudes of HRR were generally lower, exhibiting variations across test settings and intensities, and clear positive effects were observed only in the Field_{90} SMFT.

Associations between HRex during laboratory and field SMFT were very-large when considering both between- and within-athlete comparisons. Indeed, these correlation magnitudes were comparable to the intraclass correlation coefficient estimates acquired from identical, test-retest assessments performed within similar settings[7,8,20,21]. In contrast, correlation magnitudes for HRR were lower, ranging from moderate to very-large. While the source of the differences between HRex and HRR cannot be confidently ascertained from the current data, it may be reasonable to assume that they may arise from the general higher measurement variability of HRR[6,8,9], along with other extraneous factors that could theoretically affect HRR data when collected in field versus laboratory conditions (e.g., peer discussions, body posture)[6].

Regarding criterion validity, the results demonstrated large relationships for RE and laboratory HR-derived indices (90% CI indicated moderate to very-large magnitudes), but unclear associations when compared with field-based SMFT (Fig. 1, panel A and D). The difference in our findings can likely be attributed to the concomitant recording of HR measures and RE in the controlled laboratory environment, as well as various programming variables in the field based SMFT, including the exercise intensity and movement pattern. These differences may have led to distinct physiological responses such as variations in ventilation, respiratory exchange ratio, as well as increased neuromuscular loading from repeated changes of direction[22]. Notably, apart from a large association with changes in laboratory HRex (r=0.51 [0.03 to 0.80]), changes in RE were not related to changes in SMFT HR-derived indices, and coefficients were compatible with trivial effects (Table 1). This finding is interesting since we initially expected that SMFT HRex (at least in laboratory conditions) would exhibit a greater sensitivity to changes in RE because they theoretically reflect similar physiological attributes (i.e., exercise economy). However, supporting previous literature reviewing physiological and biomechanical attributes of RE[22,23], our study demonstrated that substantial reductions in HRex do not necessarily promote meaningful improvements in RE. This is partly due to the small proportion of myocardial oxygen consumption relative to whole body metabolism (1 to 2%)[22]. Additionally, factors such as ventilation and running mechanics (e.g., posture, heel strike, stride length) could have a greater influence on RE[22,23].

SMFT HRex in both laboratory and field settings showed moderate to very-large relationships with criterion measures of cardiorespiratory fitness, as illustrated in Fig. 1, panel B and C. These findings align with previously reported pooled meta-analysis, which suggested correlation ranges between –0.31 to –0.77 in subsequent studies[7]. Similarly, we observed comparable correlation magnitudes for HRR, as depicted in Fig. 1, panel B and C, which are in agreement with previous studies employing similar HRR analysis approaches (evaluating HRR separately from HRex) and examining its convergent validity, with correlations spanning a range of moderate to large relationships[6,9,21]. The greater correlation magnitudes observed in the current study is seemingly attributed to the use of laboratory-derived criterion measures, as opposed to intermittent field-based assessments that involve non-aerobic qualities contributing to test results. For longitudinal validity, changes in HRex were related to changes in maximal cardiorespiratory fitness outcomes across all test conditions (displayed in Fig. 2, panel B and C). These correlations demonstrated large to very-large negative associations, with coefficient estimates indicating that a 1-point % reduction in HRex corresponded to increases of 0.41 to 0.53 mL·kg·min^{-1} in $\dot{V}O_2$ max and 0.11 to 0.16 km·h^{-1} in MAS, as detailed in Table 1, panel A. While the coefficients estimated from the laboratory SMFT showed slight improvements compared to field conditions, the of 90% CI coverage signified negligible differences, suggesting that baseline exercise intensity has no effect on the HRex longitudinal validity. These findings likely reflect chronic positive training effects of the cardiovascular system (e.g., left ventricular function), resulting in reduced HRex at a given submaximal intensity. However, other factors, such as changes in blood volume could also contribute to the observed results. While we are as yet unaware of the true, minimum practically important difference relating to HRex, we provide practical insights by assessing its effects in relation to the 95% (4.4 % points) and 99% (5.8 % points) confidence limits of the minimum detectable change (MDC), as established in the meta-analysis of TE[7]. Regarding $\dot{V}$ max, reductions in HRex of these magnitudes corresponded to increases in $\dot{V}O_2$ max ranging from 1.8 to 2.4 and 2.3 to 3.1 mL·kg·min^{-1}, respectively. Such effects on $\dot{V}O_2$ max are comparable with the changes observed in male senior soccer players following a training intervention such as high-intensity interval training (~1.5 to 3.0 mL·kg·min^{-1})[24]. Likewise, a decrease of 4.4 and 5.8 % points in HRex were associated with improvements in MAS ranging from 0.5 to 0.6 and 0.7 to 0.9 km·h^{-1}, respectively. In practical terms, improving MAS within this lower range of magnitudes (i.e., 0.5 km·h^{-1}), such as progression from 18.5 to 19.0 km·h^{-1}, translates to additional 30 s and approximately 160 m covered between incremental treadmill tests.

The analyses of HRR longitudinal validity yielded contrasting findings. Notably, changes in HRR following Field$_{90}$ SMFT indicated a large relationship with changes in $\dot{V}O_2$ max, albeit moderate relationships with MAS. Conversely, changes in HRR following Field$_{80}$ and laboratory SMFT indicated large relationships with changes in MAS, yet relationships with $\dot{V}O_2$ max were trivial (Fig 2, panel E and F). Considering the slope coefficients, clear positive effects were observed only following the Field$_{90}$ SMFT protocol (Table 1, panel B). Although speculative, these results may suggest a higher degree of longitudinal validity for HRR following SMFTs that elicit a greater cardiovascular loading, at least bounded by the intensities we explored (approximately 80 versus 90% HR$_{max}$). A possible reason for the differences may be the reduced measurement error of HRR collected following higher submaximal intensities[8], yielding to an improved signal-to-noise ratio[9]. Moreover, unlike HR, which generally shares a linear relationship with oxygen uptake during steady-state activities, the rate of parasympathetic reactivation following exercise varies across intensities and is influenced by factors such as blood acidosis, and metaboreflex simulation[9]. These changes in parasympathetic response may also play a role in HRR measurement properties[6]. Considering the observed TE for the higher intensity field SMFT in a previous study that followed a similar protocol and collection timeframe (2.8 % points)[8], 95% and 99% confidence limits of the MDC in individual changes are 7.8 and 10.2 % points, respectively. Reductions in SMFT HRR of these magnitudes were linked to enhancements in $\dot{V}O_2$ max and MAS by 2.0 to 2.6 $mL\cdot kg\cdot min^{-1}$ and 0.3 to 0.4 $km\cdot h^{-1}$, respectively. Although there is limited evidence regarding the impact of exercise intensity on HRR, one study[25] involving well-trained triathletes observed improved sensitivity at a lower versus higher SMFT exercise intensity, albeit for assessing transient negative training effects (functional overreaching). Despite differences in cohorts and HRR analysis approaches, these observations raise questions about the role of exercise intensity in denoting positive chronic versus negative transient training effects. Therefore, future work may be necessary to gain further insight into how exercise intensity influences the measurement properties of SMFT HRR.

Acknowledging the logistical challenges in team-sports settings, the rationale for collecting resting measures in this study was to obtain further understanding on the multiple putative physiological mechanisms responsible for chronic training effects[9]. Resting HR measures have been considered as best practice for assessing ANS status, with reduced HRrest and increased vagal-related HRV possibly indicating positive effects[9]. Indeed, previous literature in a range of endurance[9] and team-sport[26,27] athletes has reported their utility as proxy measures of aerobic-oriented training effects. In the present study we found no relationships between HRrest or vagal-related HRV and aerobic performance. One possible explanation for this lack of correlation is the substantial day-to-day fluctuations observed in resting measures, particularly vagal-related HRV[9]. Therefore, to mitigate the impact of day-to-day fluctuations and attain more reliable insights, it has been recommended to collect data across multiple days and calculate an average value based on data from 3–4 consecutive days[9]. Furthermore, it's worth considering that resting HR indices might be better suited to detecting transient, short-term training effects that occur during periods of elevated training loads (e.g., congested fixture schedules) or heightened stress (e.g., exposure to extreme environmental conditions)[6,9]. Our findings further question the value of resting HR measure for assessing physiological state in team sports, particularly considering their low feasibility.

To our knowledge, this is the first study to assess intra-individual changes in SMFT HR-derived indices using an estimated trend from multiple repeated measures, rather than pre–post change scores. Whilst the increase in data points may hypothetically provide a more rigorous approach (mitigate measurement error, improve signal-to-noise ratio), further understanding is yet to be established. For example, although a range of different aggregation methods have been conceptually suggested and explored in the literature[28,29], in the current study we employed a linear function over time for analysing the slope of changes in SMFT HR-derived indices. However, it could be argued that meaningful changes in HR responses are likely to occur after a few weeks of training[6], especially in the context of a preseason phase[11]. In this regard, it may be more appropriate to analyse changes in HR measures using exponential weighted modelling. Here we also analysed the changes in HR-derived indices over a period of 6 to 8 weeks, corresponding to the preseason phase. From a practical perspective, it appears sensible that practitioners may adopt varying time windows that are aligned with the training context (e.g., in-season, rehabilitation, return-to-play phases) and periodisation strategies[30].

This study has several limitations. Firstly, the final sample size included in the longitudinal validity (within-athlete) analyses was small, thus providing less certainty around the point estimates. Here we applied robust inclusion–exclusion criteria. Therefore, in future, researchers may wish to further examine the utility of HR-derived indices (primarily HRex) to denote within-athlete aerobic training effects with larger sample sizes. Second, while strategies were employed to maintain a standardised approach preceding data collection (e.g., scheduling, training load, environmental variables, nutritional guidance), other probable extraneous factors (e.g., complementary sessions outside the team environment, possible fatigue status, plasma volume, hydration status) were not quantified. In view of this, while the overall underlying physiological mechanisms theoretically allow the generalisation of the current findings to different participants cohorts, practitioners should be conscious of other factors that are unique to specific athlete groups (e.g., menstrual-cycle moderating effects in women's team-sport athletes). It is also worth noting that integrating multiple time points for RE collection, rather than focusing on the last 60s, could offer more comprehensive insights into the relationships with HR-derived indices. Finally, and as noted previously, in the current study we used a novel approach (linear function) to identify the trend in outcomes over repeated measures, and the timeframes used to capture chronic training effects were arbitrary based on the preseason phase.

Conclusion

This study explored the utility of resting and SMFT HR-derived indices obtained from different test settings (laboratory and field) and exercise intensities, for assessing training-induced changes in cardiorespiratory fitness. The findings extend existing recommendations suggesting that HRex is a valid proxy marker of cardiorespiratory fitness status. In contrast, the utility of SMFT HRR remains elusive, and the present results indicate that its sensitivity may be impacted by the exercise intensity. Given the small number of participants, and the potential sex-specific physiological differences (e.g., influence of menstrual-cycle), future work involving larger sample sizes and different team-sport cohorts may be warranted.

Practical Applications

- HRex is a valid proxy measure of current and within-athlete training-induced effects in cardiorespiratory fitness.
- Field-based SMFT is an appropriate tool for assessing athlete’s cardiorespiratory fitness status in football.
- We propose a novel approach for monitoring SMFT HR-derived outcome measures by analysing the slopes from multiple repeated measures. Practitioners may adopt a similar approach by using different time windows, for example determined by the season stage (i.e., pre-, in-season), individualised approach (e.g., practitioners working with athletes during injury rehabilitation, eumenorrheic female athletes), and periodisation strategies.

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Table 1 changes in cardiorespiratory fitness criterion measures in relation to 1 % point decrease in HRex (panel A) and HRR (panel B) in laboratory and field settings

SMFT	**Slope**	**90% CI**	**Adjusted R^2**	**SEE**
A				
Δ RE (mL·kg·min^{-1})				
Laboratory	–0.10	–0.38 to 0.35	0.51	2.13
Field$_{80}$	–0.20	–0.46 to 0.04	0.56	2.03
Field$_{90}$	–0.21	–0.52 to 0.13	0.54	2.10
Δ $\dot{V}O_2$ max (mL·kg·min^{-1})				
Laboratory	0.52	0.07 to 1.22	0.36	2.65
Field$_{80}$	0.41	0.10 to 0.78	0.38	2.54
Field$_{90}$	0.53	0.11 to 1.30	0.38	2.51
Δ MAS (km·h^{-1})				
Laboratory	0.16	0.09 to 0.26	0.74	0.43
Field$_{80}$	0.11	0.05 to 0.23	0.61	0.53
Field$_{90}$	0.12	0.06 to 0.21	0.56	0.57
B				
Δ RE (mL·kg·min^{-1})				
Laboratory	–0.04	–0.15 to 0.10	0.50	2.18
Field$_{80}$	–0.09	–0.22 to 0.01	0.53	2.07
Field$_{90}$	–0.07	–0.23 to 0.08	0.49	2.18
Δ $\dot{V}O_2$ max (mL·kg·min^{-1})				
Laboratory	0.06	–0.18 to 0.42	0.14	3.05
Field$_{80}$	0.10	–0.13 to 0.35	0.17	2.97
Field$_{90}$	0.25	0.07 to 0.46	0.36	2.59
Δ MAS (km·h^{-1})				
Laboratory	0.04	–0.03 to 0.09	0.46	0.63
Field$_{80}$	0.03	–0.01 to 0.08	0.41	0.66
Field$_{90}$	0.04	0.01 to 0.08	0.40	0.66

CI confidence intervals, *MAS* maximal aerobic speed, *RE* running economy, *SEE* standard error of estimate, *SMFT* submaximal fitness test, $\dot{V}O_2$ *max* maximal oxygen uptake

Figure Legends

Fig. 1 Relationships between SMFT raw HR-derived indices and criterion measures of cardiorespiratory fitness. Upper (A–C) and lower (D–E) panels refer to SMFT HRex and HRR, respectively. Field_{80} indicates the first, lower intensity continuous SMFT at 11 $\text{km}\cdot\text{h}^{-1}$. Field_{90} indicates the second, higher-intensity continuous SMFT at 12.8 $\text{km}\cdot\text{h}^{-1}$.

Fig. 2 Relationships between changes (Δ scores) in SMFT HR-derived indices and criterion measures of cardiorespiratory fitness. Upper (A–C) and lower (D–E) panels refer to SMFT HRex and HRR, respectively. Field_{80} indicates the first, lower intensity continuous SMFT at 11 $\text{km}\cdot\text{h}^{-1}$. Field_{90} indicates the second, higher-intensity continuous SMFT at 12.8 $\text{km}\cdot\text{h}^{-1}$.

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Confirmation of Ethical Compliance

The research adhered to ethical guidelines outlined by the journal, with prior approval from Western Sydney University Ethics Committee (HREC number: H14606). The manuscript has been approved by all co-authors and complies with the journal's co-authorship guidelines. The research followed the World Medical Association's Code of Ethics, Declaration of Helsinki, and obtained informed consent for experimentation involving human subjects.

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CRediT author statement

Tzlil Shushan: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration. **Ric Lovell:** Conceptualization, Methodology, Investigation, Writing - Review & Editing, Visualization, Supervision. **Shaun McLaren:** Methodology, Writing - Review & Editing, Visualization, Supervision. **Martin Buchheit:** Writing - Review & Editing, Supervision. **Antonio Dello Iacono:** Writing - Review & Editing. **Adriano Arguedas-Soley:** Writing - Review & Editing. **Dean Norris:** Software, Validation, Supervision.

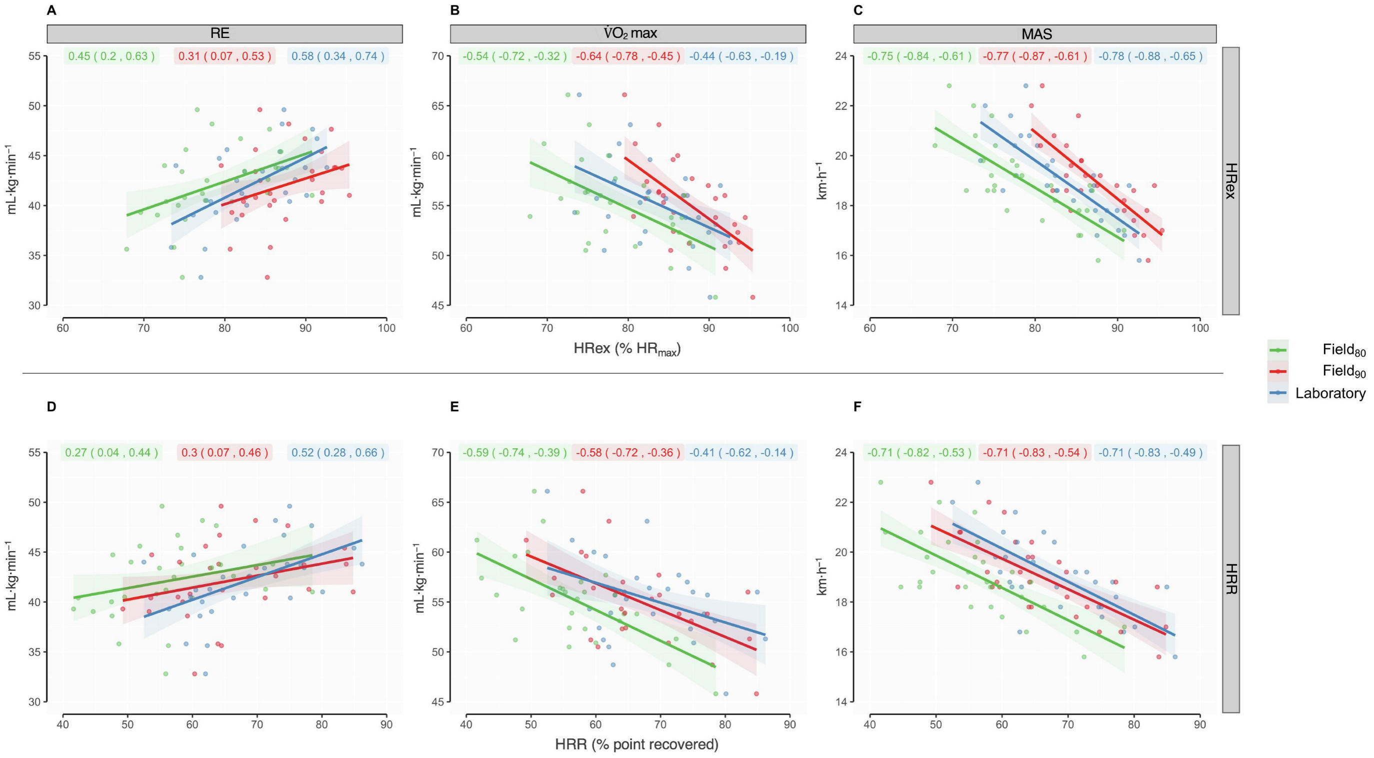
A
RE
0.45 (0.2 , 0.63)
0.31 (0.07 , 0.53)
0.58 (0.34 , 0.74)
mL·kg·min⁻¹
B
V̇O₂ max
-0.54 (-0.72 , -0.32)
-0.64 (-0.78 , -0.45)
-0.44 (-0.63 , -0.19)
mL·kg·min⁻¹
C
MAS
-0.75 (-0.84 , -0.61)
-0.77 (-0.87 , -0.61)
-0.78 (-0.88 , -0.65)
km·h⁻¹
HRex
HRex (% HRmax)
D
0.27 (0.04 , 0.44)
0.3 (0.07 , 0.46)
0.52 (0.28 , 0.66)
mL·kg·min⁻¹
E
-0.59 (-0.74 , -0.39)
-0.58 (-0.72 , -0.36)
-0.41 (-0.62 , -0.14)
mL·kg·min⁻¹
F
-0.71 (-0.82 , -0.53)
-0.71 (-0.83 , -0.54)
-0.71 (-0.83 , -0.49)
km·h⁻¹
HRR
HRR (% point recovered)
Field80
Field90
Laboratory

Figure 1

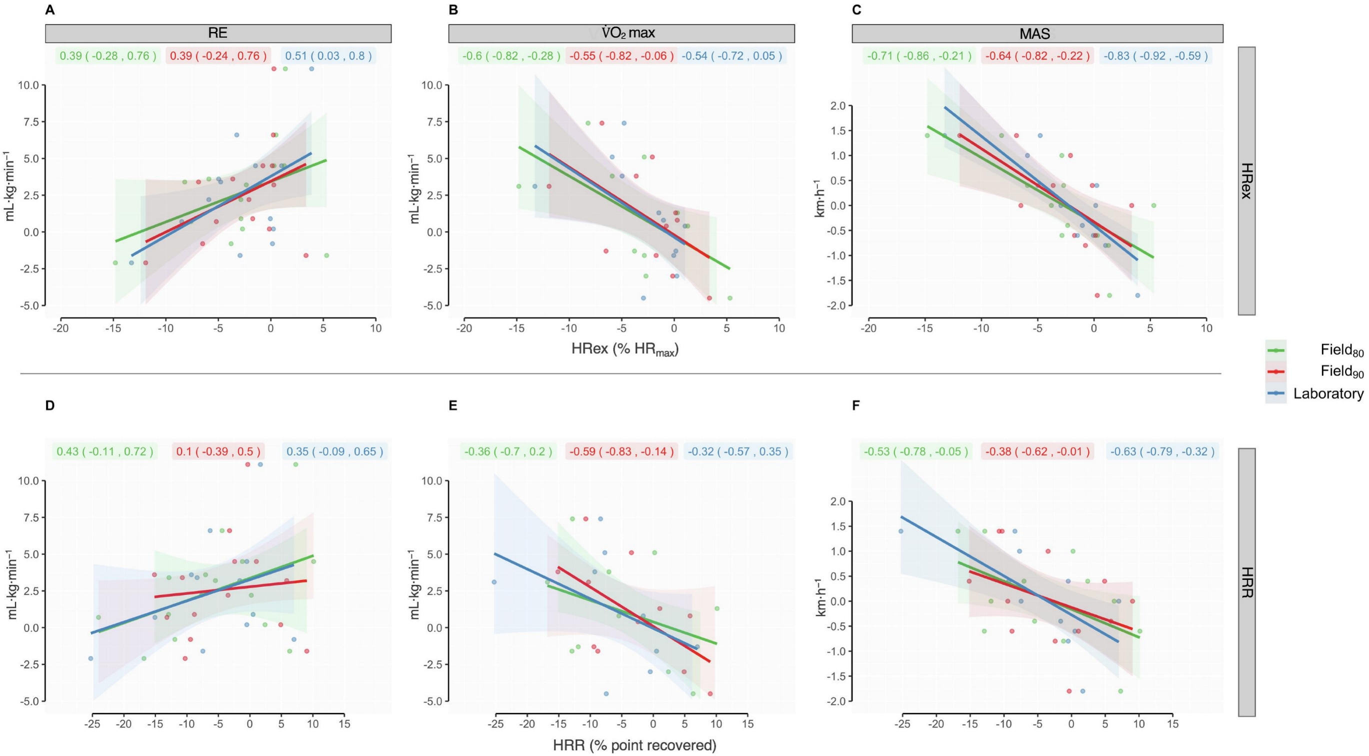
A
RE
0.39 (-0.28 , 0.76)
0.39 (-0.24 , 0.76)
0.51 (0.03 , 0.8)
B
V̇O₂ max
-0.6 (-0.82 , -0.28)
-0.55 (-0.82 , -0.06)
-0.54 (-0.72 , 0.05)
C
MAS
-0.71 (-0.86 , -0.21)
-0.64 (-0.82 , -0.22)
-0.83 (-0.92 , -0.59)
HRex
mL·kg·min⁻¹
km·h⁻¹
10.0
7.5
5.0
2.5
0.0
-2.5
-5.0
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-20
-15
-10
-5
0
5
10
HRex (% HRmax)
Field80
Field90
Laboratory
D
0.43 (-0.11 , 0.72)
0.1 (-0.39 , 0.5)
0.35 (-0.09 , 0.65)
E
-0.36 (-0.7 , 0.2)
-0.59 (-0.83 , -0.14)
-0.32 (-0.57 , 0.35)
F
-0.53 (-0.78 , -0.05)
-0.38 (-0.62 , -0.01)
-0.63 (-0.79 , -0.32)
HRR
-25
-20
-15
-10
-5
0
5
10
15
HRR (% point recovered)

Figure 2