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Minimally Invasive Ways to Monitor Changes in Cardiocirculatory Fitness in Running-based Sports: A Systematic Review

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ABSTRACT

This systematic review provides a synthesis of research investigating submaximal protocols to monitor changes in cardiocirculatory fitness in running-based sports. Following PRISMA guidelines, 2,452 records were identified and 14 studies, representing 515 athletes, satisfied the eligibility criteria. While most studies found large associations between changes in heart rate at standardized, submaximal running speeds and changes in aerobic fitness ($r = 0.51–0.88$), three studies failed to establish a relationship ($r = 0.19–0.35$). The intensity of the submaximal protocols seems to be relevant, with changes in running speeds at 90% of maximal heart rate showing larger relationships with changes in aerobic fitness ($r = 0.52–0.79$) compared to 70% of maximal heart rate ($r = 0.24–0.52$). Conversely, changes in post-exercise heart rate variability were very largely associated with changes in aerobic fitness when the testing protocols were less intense (70% of maximal heart rate) ($r = 0.76–0.88$), but not when the test required participants to achieve 90% of their maximal heart rate ($r = −0.02–0.06$). Studies on post-exercise heart rate recovery revealed inconclusive results ($r = −0.01– −0.55$), while rate of heart rate increase may be a promising athlete monitoring metric ($r = 0.08– −0.84$) but requires further research. In summary, when executed, analyzed, and interpreted appropriately, submaximal protocols can provide valuable information regarding changes in athlete cardiocirculatory fitness.

Introduction

Cardiocirculatory fitness is a critical component of performance in many sports. To produce optimal adaptations, it is paramount to establish an appropriate balance between a training load that is potent enough to sufficiently stimulate the athlete's physiological systems and a subsequent recovery period which is adequately extensive to prevent the athlete from experiencing a state of non-functional overreaching or overtraining [1]. Information on an athlete's physical response to a given training stimulus can be used to optimize performance levels by adjusting training frequency, volume, and intensity [2]. To that end, practitioners commonly use maximal or near-maximal physical fitness tests aimed at gaining further insight into an athlete's physiological determinants or sport-specific endurance capabilities [3]. However, due to the required time, resources, and their exhaustive nature, these types of tests are considered inadequate by many practitioners for frequent implementation within an applied setting as their execution might interfere with the prescribed training program or preparation for any upcoming competition [4]. Consequently, they are often employed only sparingly throughout a year at specific time points and therefore unable to detect more short-term fluctuations in an athlete's performance levels. This might in turn result in inappropriate training prescriptions and suboptimal performance levels [3].

The need for simpler and less invasive ways to assess aerobic fitness has already been a topic of discussion within the scientific literature since the 1950s, when Per-Olof Åstrand and Irma Ryhming first introduced a submaximal cycle test that aimed to predict VO_2max [5]. The Åstrand test quickly gained popularity and gave way to the development of step-, walking-, and running-based submaximal evaluations [6]. Since then, the professionalization of elite sports and the increased density of scheduled competitive events have only increased the demand for procedures that can reliably and quickly track changes in an athlete's physical condition. This has been highlighted recently in a survey on training load and player monitoring practices and perceptions in high-level soccer teams [4]. Twenty-five out of 41 respondents indicated using submaximal performance tests on a regular basis, with submaximal shuttle runs appearing to be especially popular. However, the study authors caution that interpretation of such tests is often not based on any established criteria, and as such, presents a challenge for practitioners seeking information on their athletes' training status. Ideally, protocols to be employed should be as minimally invasive as possible to make sure they can be used frequently without interfering with training and competition preparation, while being objective, reliable and sensitive to meaningful changes in performance [7].

The Lamberts and Lambert Submaximal Cycle Test (LSCT) is one example of a submaximal test that has been found to accurately reflect cycling performance [8]. Several studies have provided evidence that the LSCT is not only reliable and able to predict peak and endurance cycling performance [9, 10], but also sensitive to acute changes in training load [11] and able to reflect a state of nonfunctional overreaching in elite male and female cyclists [12, 13]. Given its relatively short duration (17 minutes), non-invasive nature and progressive increase in workload, the test can serve as a standardized warm-up and consequently can be used on a frequent basis. This allows for continuous monitoring of an athlete's fitness and fatigue responses to the current training program and aids in the prescription of upcoming training loads.

Since alterations in an athlete's training status are specific to the exercise mode [14], it is doubtful whether a cycling test such as the LSCT is a viable option for the monitoring of athletes involved in running-based sports. Therefore, it was the aim of this review to present a systematic overview of existing running-based protocols that seek to track changes in an athlete's cardiocirculatory fitness levels in a minimally invasive, easy-to-implement way. The resulting summary of available methods can help practitioners who are faced with a decision regarding which protocol might be most adequate in their specific context, while also highlighting key considerations for adequate interpretation of findings and explanations regarding common shortcomings associated with the different testing protocols.

Materials and Methods

Design and Search Strategy

A systematic review of existing literature was carried out following guidelines established in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [15]. A search of electronic databases (PubMed, Scopus, Web of Science) was undertaken by two of the authors to identify suitable original research articles published from the earliest available records up to Dec. 16, 2020. The following combination of keywords was used for the Boolean search: ("fitness monitoring") OR ("submaximal" OR "sub-maximal" OR "sub maximal") AND ("team sport" OR "soccer" OR "football" OR "running" OR "rugby" OR "AFL"). Furthermore, bibliographies of eligible articles were checked for additional relevant records. All articles were imported into a reference manager software (Mendeley 1.19.5, Elsevier, Amsterdam, Netherlands) and duplicates were removed before the titles and abstracts of all remaining records were independently screened for relevance by the two previously mentioned authors, with unsettled differences resolved in consultation with the third author. The search strategy is outlined in ▶**Fig. 1**.

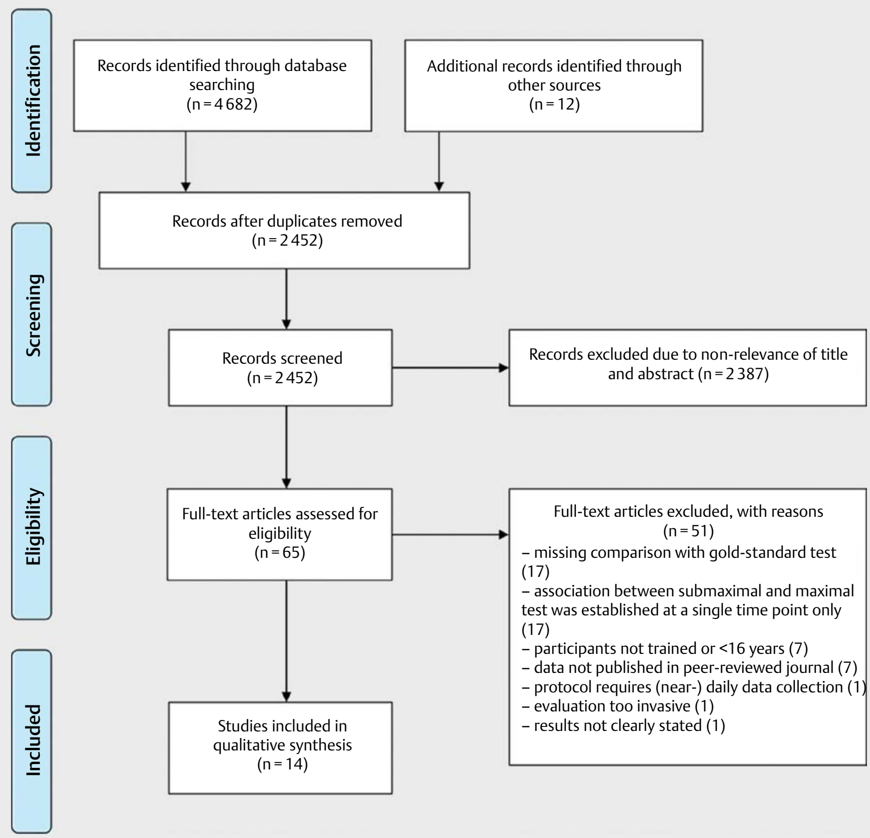
Study Selection

Study selection criteria were chosen so that the remaining testing protocols could be conceivably integrated into the daily practice of individual or team-sport athletes. Studies were eligible for inclusion in the present review, if the following criteria were satisfied:

- the study sample was comprised of healthy participants with at least 16 years of age. This minimum age requirement was established to minimize the potential influence that maturation might have on any potential target parameter [16],
- the mode of exercise for the evaluation was running,
- participants were required to be trained to a performance level of 2 or greater according to the guidelines to classify subject groups in sport science research compiled by de Pauw et al. [17] and Decroix et al. [18] (e. g. relative maximal oxygen consumption ≥ 45 $mL·min^{-1}·kg^{-1}$ for males and ≥ 37 $mL·min^{-1}·kg^{-1}$ for females),
- the evaluation was submaximal,
- results of the evaluation were compared against results from either a maximal effort endurance test or a submaximal effort endurance test with measurement of physiological parameters, such as blood lactate or expired gases (these tests were considered gold standard tests for the present review). The definition of what constitutes a gold standard test was deliberately chosen rather broadly for the purpose of the present review. While the authors acknowledge that a narrower definition might have helped facilitate (meta-analytical) comparison between the different protocols, we deemed it more beneficial to provide the reader with a more comprehensive overview of available studies on the topic. This approach allows for a critical appreciation of the main principles that the different protocols are based on,
- the association between changes in the gold standard tests and changes in the minimally invasive tests was established at two or more time points,
- the evaluation itself is based on a single test and does not require repeated data collection and trend analysis, and
- studies were published in peer-reviewed scientific journals in English language and abstracts were available for screening.

Studies were excluded from this study if any one of the following criteria was met:

- participants were exposed to altitude/hypoxic environments or heat during the study period,



▶ **Fig. 1** Preferred reporting items for systematic reviews and meta-analysis (PRISMA) study flow diagram [15].

- the submaximal evaluation was based on procedures that were deemed too invasive or time-consuming for daily use (venous or capillary blood sampling, gas exchange measurements, etc.), or
- the evaluation was used as a measure of fatigue rather than to assess aerobic fitness.

Data Extraction

Full texts of the studies included were analyzed independently by two of the authors. Population details (e. g. gender, age, training background), study details (e. g. duration, intervention, testing protocols) and a summary of key results (e. g. relationship between evaluation protocol and gold standard tests) were compiled before studies were grouped to one of two categories according to their study designs:

(1) observation of changes in heart rate (HR) response to a standardized, submaximal external output (continuous or intermittent); and
(2) observation of changes in running velocity and cardiac parasympathetic function during and after a standardized, submaximal cardiocirculatory load.

Study Quality Assessment

The methodological quality of studies included was assessed using a protocol originally proposed by Law et al. [19]. Two raters evaluated each study and independently assigned a score of 0 (study does not meet criterion), 1 (study meets criterion) or NA (item not applicable in the context of the study) to each single criterion (**Table 1S**). Finally, a percentage score was calculated based on the sum of scores achieved in relation to the number of scored items. Study quality was classified as low (≤ 50 %), good (51–75 %) or excellent (> 75 %) in line with previous analyses [20, 21]. Furthermore, Cohen's kappa coefficient (κ) was calculated to quantify the level of inter-rater agreement [22]. Due to the inhomogeneity of study approaches no meta-analytic steps were undertaken.

There was substantial agreement between raters for the quality of studies (κ = 0.63; 95 % confidence interval: 0.52–0.75). Study quality assessment scores according to Law et al. [19] are presented in **Table 1S**, ranging from 60 % to 86.7 %, with a mean score of 79.8 % ± 9.3 %, demonstrating overall excellent study quality. Items 5 (sample size justification), 7 (reliability of the outcome measures) and 16 (acknowledgment of study limitations) were the items that most studies failed to address adequately (**Table 1S**).

Results

Following the removal of duplicates, the literature search yielded a total of 2,452 records. The study selection inclusion and exclusion criteria identified 14 studies that met the specified requirements, with 12 study protocols based on a standardized, submaximal external load [23–34] and two study protocols based on a standardized, submaximal internal load [35, 36] (▶ **Table 1**).

The 14 studies represented a total sample of 515 athletes with a mean sample size of 37 ± 45 participants. The majority of studies

▶ **Table 1** Summary of studies included.

Test Principle	Authors	Population	Relevant measures	Time points of measurements	Relevant study aims	Relevant results
Observation of changes in HR responses to a standardized, submaximal external output (continuous, intermittent)	Lambert & Costill[22]	7 highly trained male college distance runners	(1) standardized progressive treadmill test to exhaustion with analysis of expired gases; (2) HR responses to submaximal 1600-m track runs at 17.6 km·h^{-1} (n = 5) or 16.2 km·h^{-1} (n = 2), which were equal to 83.1 ± 4.4 % of preseason VO2peak	(1) laboratory trials were conducted 1 week prior to the season (PRE), week 7 of the season (MID), and the week following the final competition (POST); (2) field trials were performed during preseason and 1 to 2 days prior to the competitions	investigate changes in maximal and submaximal performance indicators	all laboratory measures (VO_{2peak}, running economy, time-to-exhaustion test) improved significantly from PRE to POST ($p < 0.05$), while there were no significant differences in submaximal HR at any time throughout the season ($p > 0.05$)
	Bellenger et al.[23]	15 male runners or triathletes	(1) 5-km treadmill time trial (5TTT); (2) rate of heart rate increase (rHRI) during 5-min running tests at 8 km·h^{-1} (rHRI8km·h^{-1} - aimed to elicit 65 % of HRmax), at 10.5 km·h^{-1} (rHRI10.5 km·h^{-1} - aimed to elicit 75 % of HRmax) and 13 km·h^{-1} (rHRI13km·h^{-1} - aimed to elicit 85 % of HRmax); (3) rate of heart rate increase after 5 min of constant velocity running at 8 km·h^{-1} followed by an immediate increase for an additional 5 min at 13 km·h^{-1} (rHRI8–13km·h^{-1})	(1) at the completion of a 7-day light training period (LT); (2) after a 2-week heavy training period (HT); (3) following a 10-day taper (T)	evaluate the effect of determining rHRI at different exercise intensities to identify the intensity that permits the most sensitive tracking of changes in performance	sub-group analysis (LT, HT and T combined) revealed moderate to high inverse correlations between 5TTT and rHRI8 km·h^{-1} (r=-0.84 ± 0.22; p<0.001) and rHRI8-13 km·h^{-1} (r=-0.52 ± 0.41; p=0.049) for subjects with lower initial endurance levels; within-individual relationships between 5TTT and all other modes of rHRI in the pooled and subgroup analyses were considered either low correlations or not correlated (r=-0.24 ± 0.42 to 0.08 ± 0.18; p≥0.39)
	Nelson et al.[26]	15 male runners/ triathletes	(1) 5-km treadmill time trial (5TTT); (2) rate of heart rate increase (rHRI) during 5-min running tests at 8 km·h^{-1} (rHRI8km·h^{-1} - aimed to elicit 65 % of HRmax), at 10.5 km·h^{-1} (rHRI10.5 km·h^{-1} - aimed to elicit 75 % of HRmax) and 13 km·h^{-1} (rHRI13km·h^{-1} - aimed to elicit 85 % of HRmax); (3) rate of heart rate increase after 5 min of constant velocity running at 8 km·h^{-1} followed by an immediate increase for an additional 5 min at 13 km·h^{-1} (rHRI8–13km·h^{-1})	(1) at the completion of a 7-day light training period (LT); (2) after a 2-week heavy training period (HT); (3) following a 10-day taper (T)	determine whether analysis of rHRI over time periods shorter than 5 min improved the sensitivity of rHRI for tracking training-induced changes in endurance exercise performance	assessment of rHRI8 km·h^{-1} most consistently tracked 5TTT performance, with significant negative relationships between 5TTT and rHRI8 km·h^{-1} when rHRI8 km·h^{-1} was assessed over 2, 3 and 4 min (p=0.04 for all); significant negative relationship between 5TTT and rHRI8-13km/h (p=0.006) over 1- min period and between 5TTT and rHRI8-13 km·h^{-1} (p=0.03) over 3-min period, but no significant relationship between 5TTT and any other parameter (all p>0.05) over any other period
	Buchheit et al.[27]	19 professional male soccer players	Graded incremental treadmill test with blood lactate measurements	Players were tested on 2 or 3 occasions over 1.5 seasons	compare the changes in HR after the 12 km·h^{-1} stage (HRex) with changes in the velocity associated with the 4 mmol·L^{-1} threshold (V_{4mmol})	Large correlation between ΔHRex and ΔV_{4mmol} (r=- 0.82, CI(-0.65; -0.91))
	Altmann et al.[28]	97 professional male soccer players	Graded incremental treadmill test with blood lactate measurements	all players were tested on at least two occasions during one or two consecutive seasons	**(1)** compare the changes in HR after the 12 km·h^{-1} stage (HRex) with changes in the velocity associated with the 4 mmol·L^{-1} threshold (V_{4mmol}); **(2)** examine a range of threshold magnitudes which may improve detecting substantial individual changes	(1) different sub-group analyses provided correlation coefficients ranging between r=−0.35 to -0.72 (entire sample: r=−0.54 (95%CI (−0.45; -0.62) ; (2) thresholds of 4.5 and 6.0% were calculated for assessing substantial individual changes in fitness when examining changes in HRex and V_{4mmol}, respectively

▶ **Table 1** Continued

Test Principle	Authors	Population	Relevant measures	Time points of measurements	Relevant study aims	Relevant results
	Buchheit et al.[29]	14 moderately trained male runners	(1) maximal aerobic speed test; (2) 10 km running performance; (3) submaximal 5-min running/5-min recovery test consisting of 5 min of running at 60 % of MAS (HRex) followed by 5 min of standing recovery (post-exercise HRR and HRV)	MAS and 10 km running performance were assessed before (week 0) and after (week 9) an 8-week training intervention; the submaximal 5-min running/5-min recovery test was performed in weeks 1, 3, 5, 7, and 9	assess relationships between fortnightly HRex, post-exercise HRR and HRV indices and MAS and 10 km running performance	participants saw a large improvement in MAS (pre: 15.8 $km \cdot h^{-1}$ vs. post: 17.3 $km \cdot h^{-1}$; ES: 0.86) and a concurrent moderate decrease in HRex (pre: 146 beats.min-1 vs. post: 138 beats.min-1; ES: -0.66); participants who improved their 10 km performance time by > 0.5% (responders) experienced a large reduction in HRR (ES: -1.02) and a moderate increase in HRV (ES: 0.59); non-responders experienced trivial alterations in HRR (ES: 0.18) and HRV (ES: - 0.16)
	Buchheit et al.[30]	18 profes-sional male Australian Rules Football players	(1) submaximal 5-min running/5-min recovery test consisting of 5 min of 40-m shuttles at 13 $km \cdot h^{-1}$ (HRex) followed by 5 min of seated recovery (HRV); (2) maximal Yo-Yo IR2	(1) HRex and post-exercise HRV were assessed at the start of every training/testing session; (2) Yo-Yo IR2 was performed on the mornings of days 1, 7 and 14	examine the usefulness of a submaximal running test for monitoring training responses	ΔHRex was very largely correlated with ΔYo-Yo IR2 (r=0.88 (0.84; 0.92)); ΔHRV was very largely correlated with ΔYo-Yo IR2 (r=0.78 (0.67; 0.89))
	Malone et al.[31]	22 elite male Gaelic football players	(1) Yo-Yo IR1; (2) submaximal 5-min running/5-min recovery test consisting of 5 min of 40-m shuttles at 13 $km \cdot h^{-1}$ (HRex) followed by 5 min of seated recovery (HRR)	(1) Yo-Yo IR1 was performed at the beginning (day 1) and end (day 7) of training camp; (2) submaximal 5'/5' test was performed at the start of every training/testing session	assess the association of submaximal test parameters with changes in Yo-Yo IR1 performance	ΔHRex and ΔHRR were correlated with ΔYo-Yo IR1 (r=0.64 (90%CI (0.44;0.78)); p<0.01; and r=-0.55 (-0.33;-0.71); p<0.05, respectively)
	de Freitas et al.[32]	10 profes-sional male futsal players	(1) Yo-Yo IR1; (2) Yo-Yo IR2; (3) submaximal 5-min running/5-min recovery test consisting of 5 min of running at 9 $km \cdot h^{-1}$ along a 20 × 20-m square (HRex) followed by 5 min of seated recovery (post-exercise HRR and HRV);(4) submaximal Yo-Yo IR1 (2 min and 4 min) and submaximal Yo-Yo IR2 (2 min)	before the start of preseason (week 1) and after 5 weeks of training and competition (week 6)	analyze the sensitivity of the submaximal Yo-Yo IR and 5′-5′ tests to identify performance adaptations in futsal players and examine the potential of HR and HRV responses before, during, and after Yo-Yo IR and 5′-5′ tests to document training-induced adaptations with futsal training	significant correlations (p<0.05) between (1) ΔHR 2- min Yo-Yo IR1 and ΔYo-Yo IR1 (r=-0.68) and ΔYo- Yo IR2 (r=-0.68), (2) ΔHRV and ΔYo-Yo IR1 (r=0.76) and ΔYo-Yo IR2 (r=0.88); no significant correlations (all p>0.05) between (3) ΔHR 4-min Yo- Yo IR1 and ΔYo-Yo IR1 (r=-0.51) and ΔYo-Yo IR2 (r=-0.56), (4) ΔHR 2-min Yo-Yo IR2 and ΔYo-Yo IR1 (r=-0.56) and ΔYo-Yo IR2 (r=-0.7), (5) ΔHRex and ΔYo-Yo IR1 (r=-0.35) and ΔYo-Yo IR2 (r=-0.32), (6) ΔHRR and ΔYo-Yo IR1 (r=-0.07) and ΔYo-Yo IR2 (r=-0.19)
	Fanchini et al.[33]	24 male youth soccer players	(1) Yo-Yo IR1; (2) Yo-Yo IR2; (3) submaximal Yo-Yo IR 1 (6 min)	(1) responsiveness was assessed during 3 consecutive weeks with testing during preseason; (2) reliability was assessed during 2 consecutive weeks with testing during in-season	**(1)** examine absolute and relative reliability, SWC and MDC of submaximal Yo-Yo IR1; **(2)** examine external responsiveness of submaximal Yo-Yo IR1	(1) CV=2.2% (90%CI (1.7;2.9)); ICC r=0.78 (0.6;0.88)); SWC=0.9%; MDC=6%; (2) the correlation between change scores in the submaximal and maximal Yo-Yo versions over time was small: between ΔHR 6-min Yo-Yo IR1 and ΔYo-Yo IR1 (r=-0.21, 90%CI (-0.56; 0.16)) and between ΔHR 6- min Yo-Yo IR1 and ΔYo-Yo IR2 (r=0.19 (-0.19; 0.53))

▶ **Table 1** Continued

Test Principle	Authors	Population	Relevant measures	Time points of measurements	Relevant study aims	Relevant results
	Hulin et al.[24]	32 elite male rugby league players	(1) Yo-Yo IR1; (2) submaximal Yo-Yo IR 1 (4 min)	(1) test-retest reliability was assessed on 3 occasions, separated by 24 h (test 1 - test 2) and 7 days (test 2 - test 3); (2) players performed maximal Yo-Yo IR1 on 2 separate occasions 28.5 ± 6.5 days apart; (3) 2 maximal Yo-Yo IR1 tests were performed at the beginning of preseason and following 34 days of preseason training (n = 12)	**(1)** assess reproducibility of HR 4-min Yo-Yo IR1; **(2)** observe whether submaximal Yo-Yo IR1 is sensitive to changes in maximal Yo-Yo IR1 Performance; **(3)** calculate the magnitude of change in %HR 4-min Yo-Yo IR 1 and maximal Yo-Yo IR1 performance over time	(1) overall CV of %HR 4-min Yo-Yo IR1 was 2.4%(2;3.3%), SWC=0.7%(0.5;1%); (2) large negative relationship between Δ%HR 4-min Yo-Yo IR1 and ΔYo-Yo IR1 (r=-0.57(-0.74;-0.33)); (3) moderate increase in Yo-Yo IR1 performance from 1433 ± 304m to 1755 ± 274m (ES=1.01 ± 0.61) after 34 days of preseason training coupled with a moderate decrease in %HR 4-min Yo-Yo IR1 from 91.1 ± 3.1% to 87 ± 3.4% (ES=-1.08 ± 0.62)
	Mohr & Krus-trup[25]	172 male semi-profes-sional soccer players	(1) Yo-Yo IR2; (2) submaximal Yo-Yo IR1 (6 min)	testing performed on 4 occasions: first week of pre-season, 1 week prior to first official match, 1 week prior to mid-season break and within 1 week after the final game of the season	investigate variability in maximal and submaximal Yo-Yo performance throughout an entire season	delta changes in Yo-Yo IR2 and %HR 6-min Yo-Yo IR1 performance from pre-season to start of season, start to mid-season and mid-season to end of season were not significantly correlated (p>0.05)
Observation of changes in running velocity and cardiac parasympa-thetic function during and after a standardized, submaximal cardiocircula-tory load	Vester-inen et al.[34]	35 endurance trained men and women	(1) incremental treadmill running test with analysis of blood lactate and expired gases concentrations; (2) submaximal running test (SRT) in the field (based on LSCT), consisting of 3 stages of 6, 6 and 3 min at 70 % (stage 1), 80 % (stage 2) and 90 % (stage 3) of their HRmax and a 1-min passive recovery phase at the end; target parameters: running speed at stage 1 (RS_1), at stage 2 (RS_2), at stage 3 (RS_3) and post-exercise HRR	training consisted of an 8-week low intensity endurance training period followed by an 8-week intensive training period, with maximal treadmill evaluations performed before and after both training periods (weeks 0, 9 and 18) while subjects were asked to perform SRT on a weekly basis	investigate the capability of a novel submaximal running test to monitor changes in endurance performance during training	ΔHRR and ΔRS_1 were not significantly correlated with changes in any of the treadmill test parameters (r = -0.01–0.37), ΔRS_2 was moder-ately correlated with ΔV_{LT1} (r = 0.48; p < 0.05) and ΔV_{LT2} (r = 0.43; p < 0.05) and largely correlated with ΔVO_{2max} (r = 0.60; p < 0.01) and ΔRS_{peak} (r = 0.57; p < 0.01), ΔRS_3 was largely correlated with ΔV_{LT1} (r = 0.52; p < 0.01) and very largely correlated with ΔV_{LT2} (r = 0.74; p < 0.001), ΔRS_{peak} (r = 0.79; p < 0.001) and ΔVO_{2max} (r = 0.62; p < 0.001)
	Vester-inen et al.[35]	35 endurance trained men and women	(1) incremental treadmill running test with analysis of blood lactate and expired gases; (2) submaximal running test (SRT) on a treadmill (based on LSCT), consisting of 3 stages of 6, 6 and 3 min at 70 % (stage 1), 80 % (stage 2) and 90 % (stage 3) of their HRmax and a 1-min passive recovery phase at the end; target parameters: running speed at stage 1 (RS1), at stage 2 (RS2), at stage 3 (RS3), post-exercise HRR and HRV	training consisted of an 8-week low intensity endurance training period followed by an 8-week intensive training period, with maximal treadmill evaluations performed before and after both training periods (weeks 0, 9 and 18) and SRT performed at weeks 0, 4, 9, 13 and 18	investigate the capability of submaximal running test combined with post-exercise HRR and HRV conducted in laboratory conditions to monitor changes in endurance perfor-mance	no significant relationship (p > 0.05) between ΔVO_{2max} and ΔHRV (r = 0.06, trivial), ΔVO_{2max} and ΔHRR (r = 0.01, trivial), ΔRS_{peak} and ΔHRV (r = -0.02, trivial), ΔRS_{peak} and ΔHRR (r = -0.09, trivial) and ΔRS_{peak} and ΔRS_1 (r = 0.24, small); significant relationships between ΔVO_{2max} and ΔRS_1 (r = 0.52, large; p = 0.002), ΔVO_{2max} and ΔRS_2 (r = 0.50, large; p = 0.005), ΔVO_{2max} and ΔRS_3 (r = 0.49, moderate; p = 0.004), ΔRS_{peak} and ΔRS_2 (r = 0.40, moderate; p = 0.027) and ΔRS_{peak} and ΔRS_3 (r = 0.52, large; p = 0.002)

HR – heart rate; *VO_{2peak}* – peak oxygen consumption; *HRmax* – maximal heart rate; *5TTT* – 5-km treadmill time trial; *rHRI* – rate of heart rate increase; *HRex* – exercise heart rate; *V_{4mmol}* – running velocity associated with a blood lactate concentration of 4 mmol·L^{-1}; *MAS* – maximal aerobic speed; *HRR* – heart rate recovery; *HRV* – heart rate variability; *ES* – effect size; *CV* – coefficient of variation; *CI* – confidence interval; *ICC* – intraclass correlation coefficient; *SWC* – smallest worthwhile change; *MDC* – minimum detectable change; *RS_1* – running speed at 70 % of maximal heart rate; *RS_2* – running speed at 80 % of maximal heart rate; *RS_3* – running speed at 90 % of maximal heart rate; *RS_{peak}* – peak treadmill running speed; *V_{LT1}* – running velocity at the first lactate threshold; *V_{LT2}* – running velocity at the second lactate threshold; *VO_{2max}* – maximal oxygen consumption; *S_{peak}* – peak treadmill running speed; *S_{RCT}* – speed at respiratory compensation threshold.

was comprised of entirely male subjects, while two studies recruited both female and male participants [35, 36].

Ten studies investigated changes in exercise heart rate (HRex) at the end of a standardized, submaximal running protocol [23, 26–34], with both continuous [23, 26–28, 31] and intermittent running protocols [29–34] being evaluated. Most studies found changes in HRex to be sensitive to changes in gold-standard tests [26, 28–31, 33] (Pearson's r = 0.51–0.88), while three studies failed to establish any such relationship [23, 32, 34] (r = 0.19–0.35). Changes in post-exercise cardiac parasympathetic function were also investigated as a way to monitor fitness adaptations, with five studies investigating post-exercise heart rate recovery (HRR) [28, 30, 31, 35, 36] and four studies investigating post-exercise heart rate variability (HRV) [28, 29, 31, 36]. For submaximal running protocols based on a fixed external load, changes in post-exercise HRV (r = 0.76–0.88) [29, 31] were very largely associated with changes in gold-standard tests, while changes in HRR (r = −0.07 – −0.55) [30, 31] were inconsistent. Changes in HRV and HRR following running protocols based on a fixed internal load revealed only trivial-to-moderate associations (r = −0.01–0.37) with changes in various laboratory-derived markers of cardiocirculatory fitness [35, 36]. Two studies investigated the rate of heart rate increase (rHRI) at the onset of submaximal running as a method to assess changes in running performance [24, 25]. Results showed that rHRI may be an appropriate tool to assess changes in 5-km treadmill time trial (5TTT) performance in participants with lower initial endurance levels (r = −0.84), but not in fitter individuals (r = 0.08) [19].

Discussion

The aim of this systematic review was to provide an overview of minimally invasive methods to monitor aerobic fitness in running-based sports. An extensive range of protocols and their respective associations with maximal effort endurance tests or valid submaximal physiological parameters of endurance capacity were summarized and will be discussed in the following section.

The review identified two different categories of tests: (1) HR response to a standardized (continuous or intermittent, linear or non-linear, constant or graded) external load, and (2) running velocity in response to a standardized internal load. Given that internal training load is usually considered to be the main determinator of the training outcome [37] and since HR measures of internal load are non-invasive, inexpensive, time efficient and can be easily obtained simultaneously in many athletes with high precision [38], HR measures represent an attractive option in the athlete monitoring process. Consequently, all 14 studies included in this systematic review used HR measures to quantify the physiological response during and after exercise, with HRex being the main indicator of internal load investigated in all 14 studies.[1]

[1] At this point, the authors want to emphasize that HR during and after exercise should not be mistaken for a marker of overall internal load, but that it "merely" describes the current functional state of the cardiocirculatory system. While the measure has some major advantages, such as its ease of measurement, high measurement precision, and sound evidence of related control mechanisms, it is important to remember that it cannot provide feedback on other physiological systems that also largely contribute to the overall exercise-induced internal load.

Heart Rate Response to a Standardized Task

Exercise Heart Rate at Submaximal Running Speeds

Due to its strong association with O_2 uptake over a wide range of submaximal continuous [39] and intermittent activity [40, 41], HRex is considered a good marker of within-athlete relative exercise intensity [38]. Therefore, it has been proposed that a reduction in HRex at a standardized submaximal intensity can be considered a positive aerobic-oriented training adaptation [16]. In fact, Buchheit et al. [26] showed a very large correlation (r = −0.82) between changes in HRex after the third stage of a stepwise incremental running test (12 km·h^{-1}) and changes in the running velocity associated with a blood lactate concentration of 4 mmol·L^{-1} (V4mmol). The authors reported that in 21 out of 23 cases, when a clear (> 2x typical error) individual change in HRex was observed, a similarly clear change in V4mmol occurred, and vice-versa. Similar, albeit somewhat smaller correlations (r = −0.35 – −0.72) were reported by Altmann et al. [27] in a replication study. They expanded upon the initial study, proposing that thresholds of 4.5 and 6 % are recommended when assessing substantial individual changes in HRex at 12 km·h^{-1} and V4mmol, respectively. Using these guidelines, the authors analyzed changes in the two variables over time and identified a full agreement (both variables indicating substantial changes in the same direction, e. g. substantially reduced HRex paired with substantially increased V4mmol suggest that both variables indicate improved fitness) in 63 % of the cases, a partial agreement (substantial change in one variable, paired with an unclear change in the other variable) in 37 % of the cases and a single case out of a sample of 225 test comparisons which indicated a full mismatch (one variable indicating a substantial change in one direction, with the other variable indicating a substantial change in the opposite direction). Based on these findings, the authors of both studies suggest that a simple 3-min submaximal warm-up run might serve as a cost and time-efficient alternative to a multi-stage incremental test with repeated blood lactate sampling [26, 27]. It should be noted, however, that even though intensity and duration are the same, HRex during a single 3-min run in a field environment might be different from HRex after the third or fourth stage of a treadmill-based exercise test as was the case in the analyses by Buchheit et al. [26] and Altmann et al. [27], respectively. This assumption should be verified prior to confidently accepting a simple transferability of these lab-based findings into the field.

In a further study, 14 moderately trained male runners underwent an 8-week periodized training intervention [28]. Participants' maximal aerobic speed (MAS) and 10-km time trial performance were assessed pre- and post-intervention and a submaximal test, consisting of 5 min of continuous running at 60 % of MAS, was carried out fortnightly. From pre- to post-intervention, participants saw a moderate decrease in submaximal HRex coupled with a large improvement in MAS. Interestingly, while some participants with higher initial training status improved their MAS but did not improve their 10-km time trial performance, HRex decreased to a similar degree than participants with lower initial training status who improved in both fitness tests. This may be taken as an indication that changes in submaximal HRex can potentially be misleading with regards to (non-) adaptations in endurance capacity (i. e. 10-km time). Similarly, Lambert & Costill [23] did not find HRex at the end of a submaximal 1.6 km run to be sensitive to changes in endurance performance in seven highly trained male college distance runners throughout a competitive cross-country season. The authors reported a significant improvement in several laboratory-derived markers of endurance performance (peak oxygen consumption, running economy, fractional utilization of the aerobic capacity, time to exhaustion – all: $p < 0.05$), while HRex (and blood lactate concentration) at an estimated mean intensity of 83 % of pre-season peak oxygen consumption remained unchanged over the same period. These findings raise doubt as to whether HRex at submaximal intensities is sensitive enough to detect small but relevant cardiocirculatory and metabolic changes, especially with regards to highly trained individuals.

Several studies included in the present review investigated the association of submaximal HRex with maximal performance output during team sport-specific intermittent constant and graded running protocols. Predominantly, different versions of the Yo-Yo IR1 test [31–34] and the submaximal 5-min running/5-min recovery test [29–31] were investigated. The maximal version of the Yo-Yo IR1 test has been studied extensively and is widely used throughout a large number of different settings [42]. The studies included in this review analyzed the participants' HRex at pre-defined early stages (at 2, 4, and 6 min) of the testing protocols and established the association with the final distance achieved at maximum levels of physical exertion (gold-standard comparison). The results of the analyses were rather inconclusive, with two studies demonstrating small associations [32, 34], while two studies found large correlations between changes in the two outcome measures [31, 33]. These contradicting findings might be partially explained by comparably low levels of test reproducibility for the maximal version of the Yo-Yo IR1 test [42, 43]. Bok & Foster [43] and Schmitz et al. [42] provide overviews of all studies analyzing the different Yo-Yo tests in this regard and conclude that smaller effects on physical fitness might not be detectable using either of the Yo-Yo test variants. Furthermore, given that the maximal Yo-Yo IR1 requires a much larger contribution from the anaerobic energy system compared to the submaximal version [43], changes in anaerobic fitness could explain changes in maximal Yo-Yo IR1 performance, but would impact HRex at submaximal intensities to a much lesser extent [44].

Apart from the submaximal graded Yo-Yo tests, two studies examined submaximal constant velocity intermittent running protocols [29, 30]. Buchheit et al. [29] and Malone et al. .[30] consistently demonstrated that changes in HRex during a 40 m shuttle run test at 13 km·h^{-1} for a duration of 5 min were very largely correlated with changes in Yo-Yo IR2 performance ($r = 0.88$) during a preseason training camp in professional Australian Football players [29] and largely correlated with changes in Yo-Yo IR1 performance ($r = 0.64$) during an in-season training camp in elite Gaelic footballers [30], respectively. Based on the above results, it appears that constant velocity submaximal shuttle run protocols are more sensitive to changes in aerobic fitness than graded submaximal intermittent protocols. Nevertheless, further research is required before a more robust conclusion regarding graded versus non-graded submaximal intermittent testing protocols can be made.

In general, when evaluating HRex at submaximal intensities as a measure of aerobic fitness, it needs to be pointed out that there are various shortcomings associated with this approach. For instance, exercise intensity identified as %HRmax does not necessarily place individuals at an equivalent intensity above resting levels [45], at times resulting in noticeable differences in the %VO_2max – %HRmax association at lower exercise intensities [46, 47]. While this issue can be resolved by establishing the resting HR for each athlete to calculate individual HR reserve (HR_{Res}) ranges (which can be considered equivalent to individual VO_2 reserve (VO_{2Res}) range), several studies have shown that there can be a large discrepancy in the metabolic stress associated with the same relative exercise intensity (as quantified by %VO_2max, %HRmax, %VO_{2Res} or %HR_{Res}) between individuals [48–51]. Therefore, athletes exercising at the same %HRmax or %HR_{Res} cannot automatically be assumed to be training in the same exercise intensity domain and within-athlete changes in HRex at a given submaximal running speed might or might not indicate a switch from one exercise intensity domain to another. A further limitation relates to the interpretation of changes in HRex, given that reductions in HRex at a standardized external load cannot automatically be assumed to signal a positive cardiocirculatory adaptation. Instead, it has been demonstrated that similar reductions may also occur as a result of long-term fatigue accumulation [52]. Furthermore, there is evidence that HRex at a standardized submaximal intensity might only be sensitive to cardiocirculatory adaptations during the first three-to-six months of a training program, but not thereafter [53]. Whenever HRex at a standardized submaximal intensity is used as a marker of aerobic fitness, factors such as training status, environmental conditions or time of day can all influence the HR – exercise intensity relationship [54]. Provided that these circumstances are tightly controlled, HRex has been found to be a highly reliable measure [55] and the lowest day-to-day variations have been reported for intensities > 85 % of HRmax [56]. It has been proposed that a change in submaximal HRex of more than 3 beats·min^{-1} can be considered a meaningful change under these conditions [56].

Taken collectively, it appears that submaximal HRex can be a valid indicator of changes in cardiocirculatory fitness, especially for athletes with a lower initial training status within the first months of a training program. Based on the findings of the included studies, it seems that constant velocity protocols (e. g. 3 min of continuous running at 12 km·h^{-1} or 5 min of intermittent 40 m shuttles at 13 km·h^{-1}) should be preferred over graded protocols. Nevertheless, given that both positive and negative changes in HRex can be the result of non-performance-related circumstances (e. g. fatigue, hydration status or acute stress) [16, 52], the usefulness of HRex to detect changes in cardiocirculatory fitness is maximized when it is analyzed in the context of a larger array of monitoring tools. The suitability of submaximal HRex to monitor changes in endurance performance in highly trained athletes remains questionable, however.

Post-Exercise Heart Rate Recovery and Heart Rate Variability

Five of the studies included in this review investigated changes in post-exercise HRR [28, 30, 31, 35, 36] and four studies analyzed changes in post-exercise HRV [28, 29, 31, 36] and their respective associations with changes in aerobic fitness. HRR and HRV have attracted considerable interest over the previous decades since they represent a non-invasive and inexpensive method to gain insight into the status of the autonomic nervous system [38, 57–60]. Due to the connection of the autonomic nervous system with many other physiological systems, its responsiveness to exercise may provide useful information regarding the body's ability to tolerate exercise and/or non-exercise related stressors and in turn inform the planning of the training process [61, 62].

Vesterinen et al. investigated the association of changes in HRR [35, 36] and HRV [36] following a multi-stage running protocol based on fixed percentages of the participants' maximal HR (HRmax) with changes in various laboratory-derived markers of cardiocirculatory fitness following a 16-week training intervention. Even though previous research in well-trained cyclists demonstrated very large-to-nearly perfect correlations between changes in HRR and changes in peak power output ($r = 0.73$) and 40-km time trial time ($r = 0.96$) [63], the same could not be replicated in runners as HRR was not sensitive to changes in peak running speed in an incremental treadmill test ($r = -0.01$ and $r = -0.09$) [35, 36]. Similarly, changes in both HRR and HRV showed only trivial-to-moderate associations with changes in other performance markers, such as running velocity at the first and second lactate threshold or maximal oxygen consumption ($r = -0.01$–0.37) [35, 36]. The authors speculated that the relatively high exercise intensity (90 % HRmax) during the last 3 min of the test negatively impacted the sensitivity of HRV towards changes in cardiocirculatory fitness [38] and that the homogeneous composition of the study sample resulted in weaker associations between HRR and HRV and endurance performance [36].

While de Freitas et al. [31] did not find changes in HRR following a continuous 5-min run at 9 km·h^{-1} in 10 professional futsal players to be associated with changes in maximum Yo-Yo IR1 and Yo-Yo IR2 performance ($r = -0.07$ and $r = -0.19$), they did find that post-exercise HRV was very largely related with changes in both maximal tests ($r = 0.76$ and $r = 0.88$). Similarly, Buchheit et al. [29] showed that changes in HRV following 5 min of repeated 40-m shuttle runs at 13 km·h^{-1} were very largely related to changes in maximal Yo-Yo IR2 performance in 18 professional Australian Rules Football players ($r = 0.78$). In a further study, Buchheit et al. [28] demonstrated that both HRR and HRV were sensitive to changes in endurance capacity (i. e. 10-km time trial performance) in a sample of 14 moderately trained runners. A group of individuals responded positively to an 8-week training intervention (> 0.5 % improvement in 10-km time trial time) and experienced a concurrent large reduction in HRR and a moderate increase in HRV following a 5-min continuous run at 60 % of their MAS, while a group of non-responders experienced merely trivial alterations in both parameters.

These opposing findings might not be entirely surprising, given that Bellenger et al. [59] in a recent meta-analysis highlighted the limitations associated with using post-exercise HRR or HRV as isolated markers of athletic training status. Results of their analyses revealed that interventions which induced performance improvements were linked to concurrent increases in post-exercise HRR and HRV. However, studies leading to reductions in performance were equally associated with increases in the two parameters, highlighting that interpretation of HR-derived metrics of parasympathetic and sympathetic activity is complex and highly context-dependent. In this regard, it is important to consult additional monitoring variables such as the athlete's subjective perception of exertion to interpret changes in post-exercise HRR and HRV [11, 12].

Overall, the value of post-exercise HRR and HRV as methods to monitor changes in cardiocirculatory fitness remains questionable. HRR may be a suitable tool to track positive changes in high-intensity exercise performance, while its ability to track negative performance adaptations remains to be confirmed [38]. For the value of post-exercise HRV to be maximized, the preceding exercise intensity should be limited to below the first ventilatory threshold [36, 38]. When this was the case, changes in HRV were very largely correlated with changes in intermittent fitness tests in the studies analyzed.

Maximal Rate of Heart Rate Increase

Similarly to HRR and HRV, the HR kinetics at the onset of exercise are also controlled by and therefore indicative of the parasympathetic and sympathetic divisions of the autonomic nervous system [59]. An increase in HR acceleration may be the result of enhanced parasympathetic and/or decreased sympathetic modulation of the HR response. This may be indicative of improved exercise performance, resulting from a more rapid increase in oxygen delivery to the working muscles and thus, a reduced amount of peripheral muscle fatigue [59, 64]. In this context, rHRI describes the first derivative of the sigmoidal HR curve obtained during the transition from rest to steady-state during submaximal exercise. Two studies included in the present review examined whether rHRI was sensitive to changes in 5TTT performance [24, 25]. Bellenger et al. [24] found that the best workload for rHRI assessment in trained runners and triathletes was associated with the slowest running protocol investigated in the study, which consisted of 5 min of running at 8 km·h^{-1}. However, the authors pointed out that the association between changes in rHRI and 5TTT performance was mainly driven by a subgroup of athletes who were less conditioned ($r = -0.84$, $p < 0.001$), while this association was not significant for the pooled sample ($r = -0.24$, $p > 0.05$) or the subgroup of faster athletes ($r = 0.08$, $p > 0.05$) [24]. In a follow-up study, Nelson et al. [25] used the same dataset to investigate whether assessing rHRI over time periods shorter than 5 min improved the sensitivity to detect training-induced changes in running performance, regardless of training status. Their results showed that rHRI at 8 km·h^{-1} most consistently tracked 5TTT performance when rHRI was calculated over durations of 2, 3 or 4 min, such that for each one beat·min^{-1}·s^{-1} increase in rHRI there was an associated 5.3–5.5 second improvement in 5TTT performance.

While the body of research on parameters of HR acceleration at the onset of exercise is still relatively small, it does seem to indicate that increases in rHRI are associated with positive training adaptations and that decreases reflect negative training effects [59]. Very short running protocols (2–4 min) at very low exercise intensities (8 km·h^{-1}) seem to be ideal for assessment, making it an interesting option for athlete monitoring purposes. However, regular data analysis on a potentially large set of athletes may be more labor-intensive compared to other methods. Furthermore, additional research on larger study samples is required to further refine the testing protocols and establish its validity and reliability as a marker of athletic training status for both less trained and highly trained individuals.

Running Speed at a Standardized Internal Load

Instead of standardizing the external load and observing the associated internal response of the participants, two studies used an "inverted protocol" which standardized the internal load and looked to quantify the resulting external output [35, 36]. Using an adapted version of the LSCT, participants were required to run for 6 min at a fixed intensity of 70 % HRmax (stage 1), 6 min at an intensity of 80 % HRmax (stage 2) and 3 min at 90 % HRmax (stage 3). Following a 16-week training intervention, pre-to-post changes in the resulting running speeds were analyzed and compared to changes in various laboratory derived markers of aerobic fitness. Performing the test in outdoor conditions, changes in the running speeds at stages 2 and 3 were found to be moderately-to-very largely correlated with changes in maximal oxygen consumption (stage 2: r = 0.6; stage 3: r = 0.62), the running velocities associated with the first (stage 2: r = 0.48; stage 3: r = 0.52) and second lactate threshold(stage 2: r = 0.43; stage 3: r = 0.74) and the peak velocity achieved during an incremental treadmill test to exhaustion(stage 2: r = 0.57; stage 3: r = 0.79), while changes in running speed at stage 1 revealed only small-to-moderate associations (r = 0.24–0.34) [35]. Somewhat surprisingly, however, the same testing protocol performed under more standardized conditions on a treadmill did not result in enhanced sensitivity to track changes in peak treadmill velocity or maximal oxygen consumption (r = 0.24–0.52) [36]. This indicates that the adapted LSCT protocol can be used confidently in field conditions by runners looking to monitor training adaptations.

Accordingly, using mobile applications and HR monitors with GPS function to assess changes in the running speeds at 80 % HRmax and especially 90 % HRmax may provide valuable information regarding training adaptation. Increased running speeds may indicate positive changes, while reduced speeds may suggest a decline in running performance. While running at 90 % HRmax may not necessarily be considered minimally invasive, it has been shown that higher exercise intensities evoke more reliable outcome measures [56], and Vesterinen et al. [35] provided evidence that changes in running speeds at higher intensities are more correlated to changes in various markers of aerobic fitness. Nevertheless, as has been pointed out previously, long-term fatigue accumulation can impact the HR – exercise intensity relationship and falsely suggest performance improvements. Therefore, data on the athletes' perception of effort may be required to confidently interpret changes in any outcome variable [11, 12].

Limitations and Future Research Recommendations

One limitation of the current literature on standardized submaximal tests is that very few studies accurately report the physiological demand that is placed on the athletes during the execution of these tests. While reliability of HRex has been shown to be improved at higher exercise intensities [56], (which is a disadvantage when submaximal tests are targeted) there is evidence that protocol validity and sensitivity may be similarly enhanced by tests evoking greater internal load on the athletes. In that regard, it would be helpful if future studies quantified this load not only as a "raw" HR, %HRmax or $\%HR_{Res}$, but also in terms of the corresponding exercise intensity domain or the intensity difference to a certain intensity domain boundary. More detailed information on the evoked physiological demand of the different testing protocols would certainly be helpful in establishing whether a minimal intensity requirement exists and where it is anchored. A further limitation of the current literature pertains to the fact that the validity of many potentially interesting submaximal protocols – such as the use of subjective athlete perception of exertion [65–67], the so-called "talk-test" [68] in runners, or the integration of external and internal loads into an index of exercise economy [69] – has only been established by comparison to a gold standard marker at a single time point. There is no information available on the test sensitivity to changes across multiple time points, however. While the between-athlete comparison is an important element of a given test, we would argue that within-athlete analyses are the more pertinent issue within the context of athlete monitoring strategies. Therefore, we recommend that future studies employ a multi time point design to quantify and compare the magnitude of observed change in both the submaximal test and the gold standard test and analyze the results in the context of the typical error of measurement associated with the testing protocols. This information would greatly facilitate the interpretation of test results and allow practitioners to more confidently evaluate whether worthwhile changes in performance have or have not occurred. Finally, it is important to point out that the search strategy chosen for this systematic review has resulted in the detection of a number of different test approaches. While it was a study goal to provide the reader with a comprehensive overview of available research on the topic, this came at the expense of more strictly defined inclusion criteria. Consequently, the studies located were too heterogeneous to be validly summarized, e. g. in a meta-analytical model.

Conclusions and Practical Considerations

This systematic review provides an overview of currently existing methods and protocols that aim to monitor cardiocirculatory fitness in running-based sports in a minimally invasive way. Based on the review's inclusion and exclusion criteria, we identified, summarized, and provided context for 14 studies in an effort to inform practitioners looking for feasible protocols. The decision which protocol may be most appropriate for a given situation is very context-specific and dependent on the type of information one is looking to gather. This can range from sporadic spotcheck measurements to getting an estimate on how an athlete's fitness levels may be trending or frequent testing sessions with the goal to update exercise intensity recommendations on a near-daily basis depending on the athlete's current fitness and fatigue levels. Independent of which protocol is chosen, it seems vital that results are not interpreted in isolation, but rather considered in the context of sound physiological knowledge and a larger monitoring framework.

Monitoring changes in HRex in response to a standardized running protocol seems to be a valid option for assessing changes in endurance performance, particularly in the context of moderately trained individuals within the first months of a training program. Similarly, changes in running speeds at a fixed cardiocirculatory load appear to be largely correlated with changes in endurance performance, particularly at intensities greater than 80 % of HRmax. While higher test intensities are certainly more impactful on subsequent training performance than tests of lower exercise intensities, reliability and validity of the resulting information seems to be enhanced when a greater cardiocirculatory load is evoked. On the other hand, it seems that the validity of post-exercise HRV as a tool to monitor endurance performance is greater when the preceding running protocol is limited to intensities below the first ventilatory threshold. While analyses of post-exercise HRV might be less straightforward and more labor-intensive compared to more simple analyses of HRex and associated running speeds, the evidence presented in this review emphasizes the potential of post-exercise HRV to observe changes in cardiocirculatory fitness in a minimally invasive manner. The evidence regarding HRR as a suitable monitoring tool was inconclusive, while an analysis of rHRI showed promising results but requires further supporting evidence before more confident conclusions can be drawn.

It is outside the scope of the present review to provide an in-depth description of the methodological considerations and contextual interpretation strategies necessary when working with HR-based measures. Other review articles offer far more detail in this regard [38, 52, 58–60]. Nevertheless, we want to highlight some key considerations for practitioners intending to use minimally invasive tests to monitor their athletes' cardiocirculatory adaptations:

- Several factors (ambient temperature, athlete hydration status, time of day, etc.) can have a substantial impact on the body's response to a given standardized task. It is paramount to create testing conditions that minimize the potential impact of all sources of variability [57].
- Under standardized conditions, day-to-day variation in HRex has been found to decrease with increasing exercise intensity. While we have established that any submaximal test should be as minimally invasive and physically demanding as possible, practitioners must be aware that a decrease in exercise intensity might lead to a decreased signal-to-noise ratio [56].
- The magnitude of observed change (signal) in any outcome measure must be evaluated against the typical error of measurement (noise). In this context, it is important to quantify the magnitude of change that is required to have a practical effect (smallest worthwhile change). Ideally, the typical error of the outcome measure should not exceed the smallest worthwhile change [38, 43].
- Similar changes in HR-derived measures may indicate opposing trends in physical adaptation to chronic exercise. For example, a decrease in HRex might indicate a positive fitness adaptation but could also be the result of an overreaching-related performance impairment. Practitioners must understand and implement in their testing strategies that fatigue and performance are multifactorial constructs, and that any single metric is likely unfit to adequately capture the responsiveness of the various physiological systems [38, 52].

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The authors declare that they have no conflict of interest.

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