Durability as an index of endurance exercise performance: methodological considerations.

New Findings

- **What is the topic of this review?**

The review discusses current approaches and essential considerations for assessing physiological durability.

- **What advances does it highlight?**

The review summarises various methodological approaches used to profile the resilience to deterioration of physiological variables during or after prolonged exercise, i.e., durability. It highlights key considerations for durability profiling in research and applied settings, including exercise intensity, duration, nutritional and environmental factors, and the appropriateness of examining physiological decrements in the field or in the laboratory.

Abstract

Endurance athletes routinely complete physiological assessments to predict performance, inform training programmes, and monitor subsequent training adaptations. This profiling is typically performed with the athlete in a 'fresh' (i.e., rested) condition, but physiological profiling variables deteriorate during prolonged exercise. Durability has been defined as the resilience to the deterioration of physiological variables and performance during, or following, prolonged exercise. Herein, we review the current approaches to measure durability. The construction of the fatiguing protocol affects durability profiles, with greater relative intensity and duration resulting in more marked deterioration of baseline measures. The design of durability assessments should control for factors that could impact durability measurements, such as nutrition and environmental characteristics, to ensure outcomes are repeatable and can be compared between athletes or over time in the same athlete. The selection of these

parameters should be based on the proposed research question or applied context and take account of the training status of the athlete. Accordingly, this review highlights important considerations to ensure protocols for profiling durability in research and applied practice are appropriate.

Key words: endurance performance, fatigue resistance, exercise capacity.

1. Introduction

Endurance sports are cornerstone events in the Summer Olympic Games, capturing the attention of millions of viewers, and with athletes planning their training to achieve peak performance in their specialist event. Endurance performance is multifaceted, and affected by a range of physiological, biomechanical and psychological factors (di Prampero et al., 1986; Hoogkamer et al., 2017; Jones et al., 2021; Joyner et al., 2008, 2011; Mccormick et al., 2015). Endurance is classically considered as the ability to sustain work rate over a period ranging from ~10 min to several hours (Coyle et al., 1988). This review will focus primarily on prolonged endurance events, i.e., those lasting > 60 min.

Three physiological parameters have been used to explain much of the variation in prolonged endurance performance between athletes: maximum oxygen uptake ($\dot{V}O_{2max}$), exercise economy, and the highest sustainable fraction of $\dot{V}O_{2max}$ for a given distance, which is in turn related to the transition between domains of exercise, or so-called physiological ‘thresholds' (di Prampero et al., 1986; Jones et al., 2021; Joyner, 1991; Joyner et al., 2008; Lazzer et al., 2012; Maunder et al., 2022; McLaughlin et al., 2010). Combined, these physiological parameters determine a ‘performance speed’ (di Prampero et al., 1986; Joyner, 1991), which accounts for ~72% of the variation in marathon performance between athletes (di Prampero et al., 1986) and ~88% of the variation in a 30 min time trial (TT) following 2 hours of moderate cycling (Maunder et al., 2022).

Endurance athletes routinely measure the above physiological variables to predict performance, inform training programmes, and monitor adaptations (Maunder et al., 2021). These variables are typically assessed in a well-rested or ‘fresh’ condition and athletes limit their training beforehand. However, physiological variables often deteriorate during prolonged exercise (Clark et al., 2018; Hamilton et al., 2024; Maunder et al., 2021; Stevenson et al., 2022). For example, relative to fresh conditions, $\dot{V}O_{2max}$ has been shown to decrease following a prolonged bout of running (Unhjem, 2024), a simulated half-marathon (Dressendorfer, 1991), the first two segments of an Olympic triathlon (De Vito et al., 1995), and prolonged

cycling (Bitel et al., 2024). Similarly, gross cycling efficiency (Passfield & Doust, 2000; Stevenson et al., 2022) and running economy (Brueckner et al., 1991; Sproule, 1998; Xu & Montgomery, 1995; Zanini et al., 2024) deteriorate following prolonged exercise. Intensity domain transitions such as the first ventilatory threshold (VT_1) (Gallo et al., 2024; Hamilton et al., 2024; Stevenson et al., 2022), or critical power (CP) (Clark et al., 2018; Clark et al., 2019a, 2019b), also decay by ~10% following fatiguing exercise. Importantly, although a mean reduction of ~10% at group mean level was evident across the studies conducted by Clark and colleagues, a range of ~1-31% was observed between individuals (Jones, 2023).

Similar heterogeneity has been reported when considering performance including diminished TT power output (Hamilton et al., 2024; Ørtenblad et al., 2024; Passfield & Doust, 2000; Valenzuela et al., 2023) and peak power output (Clark et al., 2019a; Klaris et al., 2024; Spragg et al., 2024) following prolonged exercise. For example, following a ~4 hr workout, 20-min and 6-min TT performance decreased by ~2.9% (Valenzuela et al., 2023) and ~10% (Ørtenblad et al., 2024), respectively, but in both studies the authors reported a large inter-individual variability (range: –8.5% to +1.1% in Valenzuela et al., 2023) and –31% to +1% in Ørtenblad et al., 2024). Importantly, the ability to maintain power output following previous work is a key determinant of success in professional cycling (Van Erp et al., 2021).

In the same way that classical physiological parameters are associated with endurance exercise performance, the deterioration of external work rate over time is also underpinned by changes in the underlying physiology. The deterioration of $\dot{V}O_{2peak}$ (Ørtenblad et al., 2024; Unhjem, 2024), gross efficiency (Passfield & Doust, 2000), and VT_1 (Hamilton et al., 2024) are associated with a reduced capacity to produce high intensity efforts. The durability of VT_1 has also been shown to affect the ability to sustain submaximal efforts (Gallo et al., 2024). Maintaining a metabolic steady state (i.e., exercise below CP or critical speed [CS]) for prolonged periods is crucial in endurance sports like marathon running (Jones & Vanhatalo, 2017). Indeed, faster marathoner runners complete races at a higher percentage of their CS (Smyth et al., 2022; Smyth & Muniz-Pumares, 2020). Therefore, the ability to preserve, as far

as possible, fresh-state physiological parameters has important performance implications. Accordingly, durability, or resilience to prolonged exercise-induced deteriorations in physiological profiling variables during prolonged exercise (Maunder et al., 2021) has been proposed as a fourth parameter of endurance exercise performance (Jones, 2023; Maunder et al., 2021). In the 2024 Paris Summer Olympics, the cycling road races were 273 km and 158 km for the men and women, with winning times of 6:19:34 (hr:min:s) and 3:59:23, respectively. In the marathon, the men's and women's gold medallists took 2:06:26 and 2:22:55 to complete the event, respectively. Given the duration of these events, durability has clear implications for performance in several Olympic events, as well as long distance events including long distance triathlon, ultramarathons, and grand tour racing.

Whilst protocols to assess $\dot{V}O_{2max}$ (Buchfuhrer et al., 1983; Poole & Jones, 2017), intensity domain transitions (Galán-Rioja et al., 2020; Jamnick et al., 2020; Jones et al., 2019), and movement economy (Barnes & Kilding, 2015) have been discussed elsewhere, no consensus exists on durability assessment protocols. The overarching goal of this article is, therefore, to summarise current protocols to assess durability (Figure 1), with a predominant focus on physiological durability. Considerations relevant to the construction of the fatiguing protocol, and the conditions under which this protocol is performed, are also reviewed (Figure 2). We conclude by presenting key considerations to guide researchers and practitioners when designing protocols for the assessment of durability.

*** Figure 1 here ***

2. Methodological Considerations for Assessing Durability

In this section, we discuss factors that could impact the outcome of durability assessments, including the structure of physiological measures (i.e., before and after, or during exercise), the intensity and duration of the fatiguing protocol, pre- and within-exercise nutrition, and environmental conditions (summarised in Figure 2). The factors which impact durability will be dependent on the setting (i.e., research or applied practice) as well as the sporting demands.

Laboratory- or field-based methods of assessing durability will also be discussed. Inadequate control of the considerations outlined below may result in spurious findings in a research context, or inadequate profiling of durability in an applied setting.

*** Figure 2 here ***

2.1 Structure of Durability Assessment

A multitude of different tests have been used to characterise physiological durability (Table 1). We identified two main methods by which this has been administered: i) profiling *before and after* a prolonged bout of exercise, and ii) assessment of changes to physiological responses *during* prolonged exercise. These approaches can be combined by profiling responses before, during and after a prolonged, fatiguing exercise bout.

2.1.1. Before and After

Profiling *before and after* a prolonged bout of exercise can be done either on separate days or on the same day. A two-day protocol involves baseline profiling in the first session, followed by a repeat of the same tests immediately after prolonged exercise in a second session (e.g., a 3-min all out test; (Clark et al., 2018) or maximal incremental exercise test (Unhjem, 2024). Baseline measurements can also standardise the intensity of the prolonged exercise bout. A single-day protocol involves physiological profiling immediately before and after a prolonged exercise bout (e.g., a submaximal incremental exercise test; Stevenson et al., 2022). This longer assessment may be preceded by an initial characterisation trial. This can be used to improve the precision with which intensity domain transitions can be identified, particularly when using ventilatory and gas exchange data during single-day assessments (Gallo et al., 2024; Stevenson et al., 2022). Changes in physiological parameters, expressed as delta values or percentage changes, can be used to evaluate physiological durability with smaller relative or absolute differences from baseline indicating greater durability.

Measures of physiological durability during a single-day assessment may be affected by the type of physiological tests performed (Table 1). For example, an incremental exercise test to determine $\dot{V}O_{2max}$ prior to and after prolonged exercise would incorporate time within the severe-intensity domain, accelerating fatigue development (Black et al., 2017; Mateo-March et al., 2024). This complicates distinguishing the effects of the incremental exercise test itself from those of the prolonged exercise on downward shifts in physiological parameters. The combination of transient (e.g., PCr depletion; Harris et al., 1976) and sustained (e.g., glycogen depletion; Miura et al., 2000) effects of severe-intensity exercise make this approach problematic. Moreover, the restoration of physiological function following severe-intensity exercise is influenced by the nature of recovery implemented (i.e., passive or active, e.g., Yoshida & Watari, 1996), and is likely to be impacted by inter-individual variability in durability, which has been evidenced previously. Therefore, this approach does not enable confident quantification of changes to efficiency or economy during the prolonged trial. If researchers or practitioners wish to conduct assessments involving severe-intensity exercise (e.g., maximal effort incremental tests, TTs, or 3MAOT), the baseline and post-exercise assessments should be performed on separate days.

Table 1. Summary of physiological profiling methods used in durability research and the number of testing days required to profile durability.

Type	Variables assessed	Sessions recommended for durability assessment
Submaximal incremental test	Moderate-heavy transition EE GE/RE Substrate oxidation rates	One
Maximal incremental test	Moderate-heavy transition Heavy-severe transition $\dot{V}O_{2max}$/$\dot{V}O_{2peak}$ EE GE/RE Substrate oxidation rates Peak power/speed	Two
3MAOT	Heavy-severe transition $\dot{V}O_{2peak}$ W′ Peak power/speed Work performed/distance covered	Two

Time trial	$\dot{V}O_{2peak}$ (if in severe domain) Peak power/speed Mean power/speed Work performed/distance covered	Two
3MAOT: 3 min all out test, EE: energy expenditure, GE: gross efficiency, RE: running economy, $\dot{V}O_{2max}$: maximum oxygen uptake, $\dot{V}O_{2peak}$: peak oxygen uptake.		

The durability of parameters quantified at lower intensities, such as the moderate-to-heavy intensity transition or efficiency, may be appropriately determined in one session. Following a characterisation session, changes to VT_1 have previously been demonstrated during one prolonged session (Gallo et al., 2024; Stevenson et al., 2022). Submaximal incremental tests induce less metabolic perturbation than higher intensity efforts (Black et al., 2017). Unlike an incremental exercise test to task failure which can vary in length, by maintaining the same number of stages, this approach ensures a standardised volume of work done or distance covered. An initial characterisation trial is usually required to prescribe the power output or speed of the prolonged trial and the submaximal incremental test stages. Alternatively, training data may inform the intensity of the fatiguing bout (Hunter et al., 2023; Karsten et al., 2015), reducing the time burden associated with assessing durability longitudinally. In an applied setting, this permits randomisation of the testing sessions (if using a severe-intensity effort) without the need for an additional characterisation trial and would reduce the probability of a training effect occurring during durability profiling. However, in a research setting, characterisation trials or baseline measures are essential for accurately identifying intensity domain transitions and prescribing the intensity of subsequent prolonged exercise. Further to these laboratory-based approaches, field-based methods provide more practical alternatives for assessing durability.

In field-based settings, the power-duration or speed-duration relationship can be constructed from the best mean maximal power or speed thought to represent maximal efforts during training, or time trials (Hunter et al., 2023; Karsten et al., 2015; Smyth & Muniz-Pumares, 2020). These can be utilised to estimate CP and W′ prior to, and after, prolonged exercise

(Spragg et al., 2024). The "gold standard" protocol for estimating CP and W′ involves at least three exhaustive constant work-rate bouts or maximal effort TTs, with additional trials conducted if the model fit is insufficient (Caen et al., 2024; Muniz-Pumares et al., 2019). However, this protocol is cumbersome post-exercise. Performing three or more trials within quick succession risks fatigue and insufficient W′ recovery (Muniz-Pumares et al., 2019) or priming effects (Bailey et al., 2009), which will affect subsequent trials. Therefore, to construct the power-duration relationship when fresh and fatigued, six assessments would be necessary, i.e., three following prolonged exercise and three in a fresh condition, which is not practical in an applied setting.

While using two trials to estimate CP and W′ with limited rest seems appealing, caution is warranted. The linear relationship using two datapoints will always result in a perfect fit (R^2 = 1.0), and no goodness of fit parameters (e.g., standard error of the estimate or coefficient of variation (CV)) can be derived. If the shorter duration trial exhibits a greater reduction relative to the longer duration trial following prolonged exercise, this could result in an artificial increase in the resultant CP and an underestimation of W′. Extending trial durations (i.e., TTs with range of 7-20 min, instead of 2-15 min), may improve the accuracy of the 1/time model (Mattioni Maturana et al., 2018). Nonetheless, parameters from the power-duration relationship following prolonged exercise are prone to inaccuracies if methodologies diverge from recommended guidelines (Caen et al., 2024; Muniz-Pumares et al., 2019).

In summary, while both single- and multi-day protocols have the potential to provide valuable insights into durability, their suitability depends on the research question or applied context. Multi-day protocols allow for more accurate assessments by reducing confounding factors such as severe-intensity fatigue accumulation, but they are resource-intensive and less practical for longitudinal monitoring. Single-day protocols, on the other hand, are more feasible and efficient, especially in applied settings, but require careful standardisation of testing conditions to ensure reliable results.

2.1.2 Measures During Exercise

Further to assessing physiological function before and after prolonged exercise, physiological responses *during* prolonged exercise have been used to quantify durability. Durability has been quantified using decoupling of the internal-to-external work rate ratio (De Pauw et al., 2024; Maunder et al., 2021; Smyth et al., 2022). First, the ratio between internal work rate (e.g., rate of ventilation [$\dot{V}_E$] or heart rate [HR]) and external work rate (speed or power) is calculated early in a training session or competition, e.g., the 5-10 km segment of a marathon) and used as a baseline. An increase in this ratio relative to the baseline, i.e., decoupling, represents an increase in internal work rate for a given external work rate (speed or power), a decrease in external work rate for a given physiological strain, or a combination of both (De Pauw et al., 2024; Jones, 2023; Maunder et al., 2021; Smyth et al., 2022).

A recent study showed recreational marathon runners with lower decoupling ratios completed marathons faster than those with higher ratios and incorporating the magnitude and onset of decoupling reduced performance prediction error from ~6.45% to ~5.16% (Smyth et al., 2022). A similar approach has been utilised in runners when completing a “backyard ultra” comprised of 6.7-km laps, which started on the hour, every hour, until participants dropped out (De Pauw et al., 2024). Specifically, less proficient runners (i.e., those that completed less than 35 laps), exhibited significantly higher decoupling between HR and speed compared to more proficient runners (i.e., those that completed more than 35 laps). The magnitude of cardiovascular drift during 1 hr of running at 70% of $\dot{V}O_{2max}$ has also been shown to be related to training status, and greater resilience of $\dot{V}O_{2max}$ and running economy (Unhjem, 2024). However, during a marathon, HR has been shown to dissociate from both $\dot{V}O_{2max}$ and the speed which elicits $\dot{V}O_{2max}$ (Billat et al., 2022). Therefore, HR may not provide an accurate reflection of metabolic cost during prolonged exercise, although it may still represent an increase in cardiac work. Limited research has demonstrated conflicting findings regarding the relationship between HR decoupling and deterioration of rested physiological parameters (Nuuttila et al., 2024; Unhjem, 2024). Greater magnitude of HR decoupling has been shown to be associated with decreases

in $\dot{V}O_{2max}$ (Unhjem, 2024), but not with a loss speed at the first lactate threshold (LT) (Nuuttila et al., 2024). Disparate mechanistic bases for the reductions in $\dot{V}O_{2max}$ and LT may explain the conflicting findings.

Heart rate variability (HRV), which is derived from the correlational properties of HR (i.e., detrended fluctuation analysis), may be a promising avenue for monitoring exercise intensity in the field (Gronwald & Hoos, 2020; Van Hooren et al., 2023). In fresh conditions, the fractal correlation properties of R-R interval data, appear to be closely related to VT_1 in running (Van Hooren et al., 2023) and cycling (Mateo-March et al., 2023). Nuuttila and colleagues (2024) recently demonstrated an association between greater decreases in HRV during running and more marker deterioration of the speed at the first lactate threshold post-exercise. However, the calculation of HRV is sensitive to artefacts, which may limit its practical application in the field. Non-invasive wireless monitoring of muscle oxygenation (S_mO_2) has also been used to identify intensity domain transitions in rested conditions (Batterson et al., 2023). Encouragingly, the S_mO_2 associated with the moderate-to-heavy transition was consistent between pre- and post- measures following 150-min moderate cycling (Hamilton et al., 2024). However, this was only demonstrated at the group level, and within-participant coefficient of variation was high (13%). Respiratory-inductive plethysmography may also be an appropriate means of monitoring changes to $\dot{V}_E$ over time in accordance with changes to physiological thresholds (Stevenson et al., 2024). Indeed, the $\dot{V}_E$ associated with the moderate-heavy transition has been shown to remain unchanged following 90 min of running (Nuuttila et al., 2024) and 2 hr of cycling (Stevenson et al., 2024). If $\dot{V}_E$ can be monitored in real-time accurately, this could provide a means of assessing proximity to the moderate-heavy transition during prolonged exercise.

The increasing use of wearable technologies that are capable of monitoring physiological variables in real-time, and the ease of this approach, makes decoupling a promising avenue to investigate durability. It remains unclear which marker, or combination of markers, of internal work rate (e.g., HR (Smyth et al., 2022), $\dot{V}_E$ (Stevenson et al., 2024), S_mO_2 (Hamilton

et al., 2024)) should be used to assess physiological durability in the field, and what magnitude of decoupling should be exceeded to assume physiological function has started to deteriorate. Therefore, future investigations are required to ascertain which decoupling measures reflect changes to physiological function during prolonged exercise.

2.2 Exercise Intensity and Duration

2.2.1 Intensity

The intensity of prolonged exercise plays a critical role in determining durability, with higher intensities leading to earlier and greater declines in physiological parameters, such as running economy (Howe et al., 2021; Unhjem, 2024; Xu & Montgomery, 1995; Zanini et al., 2024). The disparate magnitudes of metabolic disturbance between exercise intensity domains, particularly above CP, have been demonstrated previously (Black et al., 2017; Iannetta et al., 2022; Jones et al., 2007). Prescribing the intensity of prolonged exercise based on percentages of maximal values (e.g., $\dot{V}O_{2max}$), is questionable and should be discouraged (Iannetta et al., 2020; Lansley et al., 2011; Meyler et al., 2023). Athletes may operate in different intensity domains, each eliciting unique metabolic (Black et al., 2017; Iannetta et al., 2020; Lansley et al., 2011; Meyler et al., 2023) and neuromuscular (Brownstein et al., 2021) responses to exercise, which in turn may affect durability.

Recent research supports the notion that exercise intensity plays a crucial role in durability profiling, demonstrating that the amount of accumulated work above LT is moderately related to the loss of TT power (Klaris et al., 2024). When considering differences between severe and moderate exercise intensities, bouts of either moderate intensity (70% of CP) or a repeated high-intensity protocol (5 × 8 min at 105%–110% of CP) resulted in different levels of durability depending on the intensity of the previous exercise (Spragg et al., 2024). Indeed, most cyclists in the study were classified as “fatigable” having exhibited reduced power outputs following both high-intensity and low-intensity protocols. However, four of the 13 cyclists

demonstrated more pronounced reductions in power output specifically following the high-intensity protocol, with these reductions being more substantial during shorter duration power outputs. Similarly, Mateo-March et al., (2024), found that even small amounts of work above CP (2.5 $kJ \cdot kg^{-1}$) resulted in greater decreases of maximal mean power and CP when compared to work-matched exercise performed below CP. MacDougall and colleagues (2024) provide further evidence for the role of greater metabolic disturbance in the reduction of performance. Performing intervals (10 × 2 min at 80% peak power) induces greater metabolic and contractile dysfunction when compared to low-intensity constant work-rate exercise. It has also been shown that heavy, but not moderate, intensity exercise significantly reduces $\dot{V}O_{2peak}$ and peak power output during subsequent exercise (Brownstein et al., 2022).

Considering these findings, to ensure consistency in a research context, exercise should be standardised to intensity domain transitions. Previous studies used exercise intensity domains as a framework to regulate intensity during prolonged exercise (e.g., Clark et al., 2018; Clark, et al., 2019a, 2019b; Gallo et al., 2024; Hamilton et al., 2024; Nuuttila et al., 2024; Spragg et al., 2024; Stevenson et al., 2022). Using a constant work rate permits repeated intermittent or continuous measurement of physiological data in a “steady state” and may permit researchers to draw firmer conclusions about the aetiology of fatigue, and therefore inferences about durability. However, constant work-rate bouts do not adequately mimic the demands of competition, which tends to be stochastic in nature (Klaris et al., 2024; van Erp & Sanders, 2021).

In an applied context, and in research where within-participant variation is of interest, it may be more appropriate to exercise at an absolute power output or speed, for the same duration, to determine changes to durability over time (Matomäki et al., 2023). This method is standard practice when examining changes to running economy over time (e.g., Jones, 2006) and has been utilised to quantify changes to durability (Matomäki et al., 2023). Power or speed may periodically be updated in line with durability characteristics to ensure some deterioration in resting markers of performance or physiology. However, if a change to the speed or power

corresponding to intensity domain transitions is expected, it is important to evaluate whether the speed or power of the fatiguing bout should be adjusted accordingly. This would ensure that improvements can be attributed to better durability rather than the work being completed at a lower relative intensity. Finally, for the purposes of talent identification, the approximate power output or speed expected within a competitive environment could be used for the prolonged bout. This would permit the identification of resilient or durable individuals that are able to maintain rested physiological parameters in the face of competitive demands.

2.2.2 Duration and Volume

Previous research has examined changes to physiological function over a range of time periods (e.g., 30 min (Fullerton et al., 2021) to 24 hours (Gimenez et al., 2013). Clark et al. (2019a) demonstrated that 40 and 80 min of cycling in the heavy domain had no effect on CP, but after 120 min of cycling CP decreased by ~10% on average. A significant reduction of W′ from baseline occurred earlier, with a linear reduction that became significant after 80 min (Clark et al., 2019a). Similarly, power output at VT_1 declined in a non-linear fashion during prolonged cycling in the moderate domain (Gallo et al., 2024). Importantly, the onset of this decline differed substantially at the individual level and was related to time-to-task failure. Therefore, when profiling durability, consideration should be given to the length of the prolonged exercise bout.

Computing the total amount of work completed (or distance covered in running) accounts for both intensity and duration and thus appears to be an attractive candidate to standardise protocols. Several studies have employed this approach, particularly in cycling, where the power-duration profile has been determined in athletes after a certain amount of work has been accumulated (Mateo-March et al., 2022, 2024; Muriel et al., 2022; Valenzuela et al., 2023). However, recent findings suggest that durability is more strongly influenced by the work performed in the heavy and severe intensity domains rather than by the total accumulated work (Klaris et al., 2024; Leo et al., 2022; Spragg et al., 2024). When comparing durability between athletes with different baseline performance capacities, such as speed at LT or CP,

comparisons based on specific distances or work completed may provide meaningful insights in a research setting. For example, if two runners of varying performance levels are prescribed a 90-min run at LT, the faster runner will cover a greater distance, potentially leading to greater deterioration in physiological parameters. Differences in durability profiles, such as running economy, have indeed been observed between athletes when distance is the constant factor and intensity is matched (Zanini et al., 2024). This method may be less applicable when considering real-world performance and may be more useful in a research setting. Notably, "highly successful" athletes tend to show less pronounced declines in performance after fixed amounts of work compared to "less successful" athletes (Van Erp et al., 2021). The timing of either performance bouts or physiological tests also warrant consideration. For sports that involve sporadic bouts of high intensity work, e.g., intermediate sprints, or very long exercise durations, it would be prudent to include multiple time points where durability can be profiled (e.g., Gallo et al., 2024; Klaris et al., 2024) This would enable practitioners to derive more specific profiles to inform pacing or other interventions.

In summary, the intensity and duration of the fatiguing bout are important factors which have been shown to influence the downward shift in performance and physiological parameters. The choice of these factors together should result in prolonged exercise which is demanding enough to observe changes from resting measures and will depend on the competitive level of the athlete (Van Erp et al., 2021). Failure to elicit a downward shift in physiological parameters from rest may result in an inability to draw meaningful conclusions about an intervention. For example, Sánchez-Redondo et al. (2024) recently investigated the efficacy of caffeine ingestion on 8-minute TT performance following 20 $kJ \cdot kg^{-1}$ moderate-intensity cycling. However, TT performance showed no significant differences between the caffeine and placebo conditions when compared to the fresh condition. As a result, the authors were not able to resolve the ergogenic effects of acute caffeine intake on TT performance following prolonged exercise. Pilot testing may be necessary to ensure the fatiguing bout elicits a deterioration of the performance or physiological markers of interest. Given the propensity for

some individuals to exhibit little change from baseline values following a fatiguing bout, pilot testing using a group may be useful to examine the range of responses. The duration of the bout should remain consistent between individuals and over time when testing longitudinally.

2.3 Nutritional availability

The energy demands of endurance events are satisfied, primarily, through oxidation of fats and carbohydrates. The relative contribution of fat and carbohydrate oxidation is, in turn, determined by the intensity and duration of exercise and can be influenced by nutritional strategies (Podlogar & Wallis, 2022; Romijn et al., 1993). It is plausible that nutritional status and, specifically, carbohydrate availability, play a role in durability (Clark et al., 2019a; Dudley-Rode et al., 2024; Ørtenblad et al., 2024; Spragg et al., 2024). For example, carbohydrate ingestion ameliorates the decline of CP (Clark et al., 2019a) and VT_1 (Dudley-Rode et al., 2024) during prolonged cycling. The rates of carbohydrate oxidation and fat oxidation have been implicated in the decline of CP and W′ but reductions in CP were not significantly correlated with changes in muscle glycogen concentration (Clark et al., 2019a). However, greater decreases in W′ were associated with more extensive glycogen depletion (Clark et al., 2019a). More recently, Ørtenblad et al. (2024) demonstrated weak associations between peak fat oxidation as well as fat oxidation over the first three hours of exercise, and durability in elite cyclists. However, higher fat oxidation rates in the fourth hour of exercise were associated with greater reduction of mean power output during a 6-min maximal TT following 4 hr of cycling (Ørtenblad et al., 2024). The greater reliance on fat oxidation may be attenuated through strategies aimed at glycogen sparing (e.g., carbohydrate intake during exercise). Despite these findings, methodological differences regarding nutritional intake exist between studies. For example, in some studies, athletes consumed carbohydrates during prolonged exercise (Bitel et al., 2024; Klaris et al., 2024; Ørtenblad et al., 2024; Spragg et al., 2024), whereas in others, athletes were not allowed to consume carbohydrates (Clark et al., 2018; Stevenson et al., 2022; Unhjem, 2024; Zanini et al., 2024).

Carbohydrate ingestion during, or prior to, exercise reduces fat oxidation during exercise and reduces depletion of liver glycogen stores (Gonzalez et al., 2015; Jeukendrup et al., 2006; Podlogar & Wallis, 2022). Differences in substrate oxidation have previously been shown to be related to durability (Gallo et al., 2024; Ørtenblad et al., 2024; Spragg et al., 2023a). For example, the time to a 5% reduction in VT_1 is associated with greater fat oxidation and lower carbohydrate oxidation rates during cycling (Gallo et al., 2024). Therefore, changes to diet or carbohydrate intake during exercise may hinder the ability to draw firm conclusions about athletes' progress in applied practice or result in spurious findings in a research setting. It is recommended that carbohydrate ingestion, both pre- and within-exercise, remains consistent between testing sessions. Despite the lack of empirical evidence, there is potential for other nutritional ergogenic aids to influence durability. For example, caffeine has been shown to improve prolonged cycling performance (Spriet et al., 1992) and 7 $kJ \cdot kg^{-1}$ TT performance following prolonged cycling (Cox et al., 2002). Nitrate is a potential candidate for improving durability, as it attenuated the rise in $\dot{V}O_2$ and the fall in muscle glycogen concentration during 2-hr moderate-intensity cycling, albeit without influencing performance in a subsequent 4-km TT (Tan et al., 2018). Nonetheless, given the potential for nutritional ergogenic aids to impact performance, it is recommended that the use of nutritional ergogenic aids is consistent between durability testing sessions. Finally, care should be taken to ensure participants begin testing in a euhydrated state. It is recommended that athletes consume water ad libitum throughout durability assessments to mitigate negative effects of dehydration (Goulet & Hoffman, 2019).

2.4 Environment

Physiological testing is normally performed in temperature-controlled laboratories, but athletic events often take place in more extreme environmental conditions. It is well established that altitude (Deb et al., 2018; Hamlin et al., 2015) and heat stress (Kuo et al., 2021; Wingo et al., 2020) have ergolytic effects on endurance performance. There is currently a lack of

information available as to whether durability is also sensitive to environmental conditions, and whether compromised durability plays a role in the decrease in performance observed during exercise in challenging environments. However, the negative impact of hypoxia appears to be greater over longer distances (Deb et al., 2018). When cycling and running in 35°C, greater cardiovascular strain and a larger reduction of $\dot{V}O_{2max}$ was observed after 45 min compared to 15 min (Wingo et al., 2020). However, similar repeated measures studies with a control condition in temperate environments are needed to evaluate the effects of thermal stress on durability. Some laboratories have incorporated physiological testing in temperate and extreme environmental conditions, which better represent the actual racing conditions of athletes (e.g., Bell et al., 2017; Bourgois et al., 2022). Due to the paucity of literature in this area, it is recommended that future research investigates the effects of environmental conditions on durability. In field studies, the control of environmental factors is difficult. For practitioners or researchers wishing to track durability over time, testing under similar environmental conditions is recommended to ensure changes to durability are not influenced by differences in thermal stress. If researchers wish to compare means at the group level, care should be taken to ensure similar environmental conditions during testing in the field. If performance prediction is of importance, we advocate for testing to be conducted under conditions that correspond to those that are expected during the competition being trained for.

2.5 Laboratory-based vs field-based measures

Field-based measures allow data collection in ecologically valid environments, often requiring fewer resources, and can be utilised during training or competition. This approach permits ongoing monitoring of durability across a competitive season (Spragg et al., 2023b) and within races (De Pauw et al., 2024; Smyth et al., 2022) using wearable technology. For instance, retrospective analyses of power meter data have been performed to differentiate the performance category within a group of elite athletes (Van Erp et al., 2021). However, this method relies on maximal efforts being performed either naturally during training or

deliberately for testing purposes. Conducting TTs both in a fresh condition and after accumulating work ensures the inclusion of maximal efforts in durability profiling, providing a more rigorous approach for estimating CP and W′ (Spragg et al., 2024). Another field-based method, decoupling of the internal-to-external work rate ratio, has been proposed to quantify physiological drift (De Pauw et al., 2024; Maunder et al., 2021; Smyth et al., 2022). This could be achieved either during competition, or during a controlled bout of exercise during training, to measure physiological drift (internal work rate) relative to speed or power (external work rate). TTs prior to and after accumulated work, or measurement of internal-to-external work rate, can both be executed during a controlled bout of exercise during training. While such approaches facilitate longitudinal durability monitoring, field-based testing may be influenced by variables like tactics, pacing strategies, motivation, and environmental conditions. Additionally, during cycling, factors such as cadence (Barker et al., 2006), position (i.e., upright vs. time trial position; Kordi et al., 2019), and terrain (i.e., flat vs. uphill; Nimmerichter et al., 2015) should be monitored or controlled during the trials to minimise variability in physiological responses.

In contrast, laboratory-based testing provides a controlled environment ideal for examining the mechanistic underpinnings of durability. Researchers and practitioners can precisely alter the metabolic perturbation through modifying duration (Clark et al., 2019a), intensity (Brownstein et al., 2022; Leo et al., 2022; Spragg et al., 2024), and nutritional intake (Clark et al., 2019a; Dudley-Rode et al., 2024). While this approach may lack ecological validity, if factors such as intensity and duration are not controlled, durability cannot be tracked accurately over time. Furthermore, alterations to hypoxic and environmental conditions are feasible to closely mimic competitive environments such as might be anticipated in, for example, the Summer Olympics. However, laboratory-based tests may be problematic when conducting performance tests alongside durability, particularly in running. TTs more closely replicate the demands of competition, whereas square wave time-to-task failure trials often lack specificity. Electromagnetically-braked cycle ergometers or smart trainers permit the performance of TTs

following a prolonged bout of exercise (Hamilton et al., 2024). Mixed reproducibility of TTs has been reported previously when performed on motorised treadmills (Doyle & Martinez, 1998; Russell et al., 2004; Schabort et al., 1998). To account for this, we recommend conducting familiarisation trials if measures of performance are of interest in a laboratory setting. Furthermore, it may not be practical to test athletes after prolonged bouts of exercise to measure changes in physiological or performance in a laboratory setting due to either time or resource constraints.

A potential avenue which has received little attention in the literature is to conduct the prolonged exercise bout in a quasi-controlled environment outdoors before proceeding with laboratory-based measurements (Bitel et al., 2024; Brueckner et al., 1991; Dressendorfer, 1991; Klaris et al., 2024). Cyclists recruited by Klaris et al. (2024) and Bitel et al. (2023) completed physiological profiling before and after 6 hr and 90 min of outdoor cycling, respectively. Such an approach permits the rigour of laboratory-based testing for the assessment of physiological phenomena alongside more ecologically valid fatiguing protocols. However, this paradigm may not adequately replicate the profile of races or permit control of environmental factors. Moreover, and as noted by Bitel et al (2023), the transition time from the fatiguing bout to subsequent testing may result in metabolic and energetic reconstitution. Shorter times to post-exercise assessments have been associated with a much greater reduction in neuromuscular function (Brownstein et al., 2021). Therefore, the transition time from field to laboratory should be standardised between athletes and between visits to ensure consistency.

Predicting durability characteristics from traditional baseline measures offers a potentially time-efficient alternative to laboratory-based durability testing. Efforts in this area have yielded mixed results (Jones, 2023; Ørtenblad et al., 2024; Spragg et al., 2023a). For example, Spragg and colleagues (2023) demonstrated excellent predictive capability of the change in CP, but not W′, following 5 x 8-min efforts at 105-110% CP using relative $\dot{V}O_{2max}$, gross efficiency, carbohydrate oxidation, and fat oxidation in a multiple linear regression analysis.

However, the change in CP following 2 hr of heavy intensity cycling in the studies of Clark and colleagues was not significantly correlated with fresh measures of $\dot{V}O_{2max}$, gas exchange threshold, CP, or W′ (Jones, 2023). Additionally, no significant correlations were reported between the change in mean 6-min power output after a 4-hr intermittent cycling protocol and laboratory measures (i.e., LT, gross efficiency, fat oxidation, and $\dot{V}O_{2peak}$; (Ørtenblad et al., 2024). These discrepancies may stem from differences in fatiguing protocols and nutritional status, underlining the need for further research to clarify potential links between rested laboratory parameters and durability.

3. Conclusions

A large proportion of the observed inter-individual variation in endurance exercise performance can be explained by $\dot{V}O_{2max}$, exercise economy, and metabolic thresholds. However, these indices of endurance performance deteriorate with prolonged exercise and, therefore, performance capacity also decreases. Durability, which is defined as the ability to preserve physiological function during prolonged exercise, is an emerging component of endurance performance. Unlike traditional markers of endurance performance, the quantification of durability has not been standardised, and so far, durability has been evaluated through a range of physiological and performance approaches. Physiological approaches to evaluate durability include the assessment of physiological characteristics at rest and following prolonged exercise, or quantification of the decoupling of the internal-to-external work rate ratio during exercise.

In summary, factors including exercise intensity and duration, nutritional status, and environmental status have the potential to influence durability. The best practice for the profiling of durability will depend on the intended application and the context. We encourage practitioners and researchers to take account of the considerations highlighted in Figure 2 and discussed throughout this review, prior to profiling durability in athletes and participants. We

hope that greater rigour in the protocols employed, and more consistency in the approach taken by both researchers and applied practitioners in this emerging field, will result in a greater collective understanding of the physiology underpinning, and the interventions that might enhance, durability during endurance exercise.

Tables and Figures Captions

Figure 1. Summary of the different approaches to quantify durability (physiological and performance) and the considerations to be made when profiling durability.

Figure 2. Flow chart outlining key considerations to be made when profiling durability.

Table 1. Summary of physiological profiling methods used in durability research and the number of testing days required to profile durability.

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