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INVITED REVIEW

Orthostatic testing for heart rate and heart rate variability monitoring in exercise science and practice

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Abstract

Orthostatic testing, involving the transition from different body positions (e.g., from lying or sitting position to an upright or standing position), offers valuable insights into the autonomic nervous system (ANS) functioning and cardiovascular regulation reflected through complex adjustments in, e.g., measures of heart rate (HR) and heart rate variability (HRV). This narrative review explores the intricate physiological mechanisms underlying orthostatic stress responses and evaluates its significance for exercise science and sports practice. Into this matter, active orthostatic testing (e.g., active standing up) challenges the cardiovascular autonomic function in a different way than a passive tilt test. It is well documented that there is a transient reduction in blood pressure while standing up, leading to a reflex increase in HR and peripheral vasoconstriction. After that acute response systolic and diastolic blood pressures are usually slightly increased compared to supine lying body position. The ANS response to standing is initiated by instantaneous cardiac vagal withdrawal, followed by sympathetic activation and vagal reactivation over the first 25–30 heartbeats. Thus, HR increases immediately upon standing, peaking after 15–20 beats, and is less marked during passive tilting due to the lack of muscular activity. Standing also decreases vagally related HRV indices compared to the supine position. In overtrained endurance athletes, both parasympathetic and sympathetic activity are attenuated in supine and standing positions. Their response to standing is lower than in non-overtrained athletes, with a tendency for further decreased HRV as a sign of pronounced vagal withdrawal and, in some cases, decreased sympathetic excitability, indicating a potential overtraining state. However, as a significant main characteristic, it could be noted that additional pathophysiological conditions consist in a reduced responsiveness or counter-regulation of neural drive in ANS according to an excitatory stimulus, such as an orthostatic challenge. Hence, especially active orthostatic testing could provide additional information about HR(V) reactivity and recovery giving valuable insights into athletes' training status, fatigue levels, and adaptability to workload. Measuring while standing might also counteract the issue of parasympathetic saturation as a common phenomenon especially in well-trained endurance athletes. Data interpretation should be made within intra-individual data history in trend analysis accounting for inter-individual variations in acute responses during testing due to life and physical training stressors. Therefore, additional measures (e.g., psychometrical scales) are required to provide context for HR and HRV analysis interpretation. However, incidence of orthostatic intolerance should be evaluated on an individual level and must be taken into account when considering to implement orthostatic testing in specific subpopulations. Recommendations for standardized testing procedures and interpretation guidelines are developed with the overall aim of enhancing training and recovery strategies. Despite promising study findings in the above-mentioned applied fields, further research, thorough method comparison studies, and systematic reviews are needed to assess the overall perspective of orthostatic testing for training monitoring and fine-tuning of different populations in exercise science and training.

Keywords Orthostasis · R–R intervals · HRV · Autonomic nervous system · Monitoring · Endurance training

Abbreviations

ANS	Autonomic nervous system
BP	Blood pressure
CO	Cardiac output
CV	Coefficient of variation

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DFAa1	Short-term scaling exponent of detrended fluctuation analysis
HF	High frequency
HR	Heart rate
HRV	Heart rate variability
LF	Low frequency
POTS	Postural tachycardia syndrome
PPG	Photoplethysmography
RAAS	Renin–angiotensin–aldosterone system
RMSSD	Root mean square of successive differences of normal-to-normal R–R intervals
SD	Standard deviation
SD1	Standard deviation 1 from the Poincaré Plot
SDNN	Standard deviation of normal-to-normal R–R intervals
SV	Stroke volume
SWC	Smallest worthwhile change
ULF	Ultra-low frequency
VLF	Very-low frequency
Δ t	Time to peak HR

Introduction

In exercise science and practice monitoring of internal and external load markers (including resting physiology) is an essential part of the training process to address (the adaptation of) programming of specific load and recovery measures (Borresen and Lambert 2009). Successful approaches should lead to specific acute and chronic responses (adaptation), performance, and capacity improvements also ensuring a good state of overall health. While it is beyond the scope of this narrative review to provide a comprehensive overview of monitoring approaches, recently a fine-tuning approach has been proposed by Boullosa et al. (2023) to implement several valid and practical tools, instead of relying on a single parameter or tool, to improve the effectiveness of monitoring practices when added to the knowledge of an interdisciplinary expert group in sports research or practice. The choice of a combination of adequate tools and parameters for monitoring purposes within this fine-tuning approach in load and recovery management may support evidence-informed decision-making, by integrating both scientific evidence and methodological simplicity and practicality for the sport-specific conditions and underlying circumstances.

In this context, monitoring of cardiovascular autonomic nervous system (ANS) functioning and corresponding outcome measures of heart rate (HR) and HR variability (HRV) have a long tradition to complement such fine-tuning approaches (Aubert et al. 2003; Billman 2011; Buchheit 2014; Michael et al. 2017; Ernst 2017a; Lundstrom et al. 2023). HR is defined as the number of heartbeats per minute and HRV describes the beat-to-beat fluctuations of time intervals between adjacent heartbeats over a defined measurement period and reflects the dynamic end-organ response of the heart to physiologic and/or pathophysiologic perturbations, as well as environmental influences (Billman 2011; Gronwald et al. 2024). Further, HR and HRV are primarily generated by the non-linear interaction of the efferent positive chronotropic influence of the sympathetic, the negative chronotropic influence of the parasympathetic branch of the ANS, the intrinsic activity of the hearts pacemaker cells, and further internal and external non-neural factors that reflect the context-dependent psycho-neuro-endocrinological modulation of cardiovascular control according to the demands imposed on the organism (Benarroch 1993; Persson 1996; White and Raven 2014; Michael et al. 2017). This complex modulation integrates several feedforward and feedback mechanisms that act on different time scales depending on psycho-physiological demands and cardio-postural interaction (e.g., arterial and muscle-pump baroreflex, respiratory control, circulating catecholamines, muscle metabo-/mechanoreflex, and renin–angiotensin–aldosterone system) and is therefore related to the individual dynamic regulation of circulatory control of HR and arterial blood pressure.

In the subsequent sections, we will provide a short overview about HRV metrics and resting measurements including the application and potential of postural change maneuvers, known as orthostatic testing, as an autonomic challenge of interest. We will also provide an overview about the physiological background of postural change mechanisms and the application in exercise science and sports practice. The present narrative report aims to (1) describe the relevance of the cardiovascular autonomic mechanism behind orthostatic testing for sports medicine and exercise science, to (2) resume and discuss the available evidence on advantages and limitations implementing such an orthostatic testing approach for training monitoring and fine-tuning in exercise science and training applications, and to (3) give a short introduction how a standardized approach for the specific field could look like and might be further evaluated in future studies.

Heart rate variability metrics: a short overview

From a methodological point of view, the time series of successive R–R intervals (based on the detection of the R-waves in PQRST complexes of the electrocardiogram as gold standard assessment; Hurst 1998; Task Force 1996), the so-called "tachogram" builds the basis from which various metrics with different time intervals are derived (e.g., from ultra-short-term around 1 min, short-term around 5 min and longer up to long-term with 24 h depending on the context and field of application; Task Force 1996; Berntson et al. 1997; Achten and Jeukendrup 2003; Sassi et al. 2015; Sammito & Böckelmann 2015; Ernst 2017b; Shaffer and Ginsberg 2017). For that purpose, different HRV metrics of time-, frequency-, and/or non-linear domains are widely used as markers of human cardiovascular health and risk stratification (Thayer et al. 2010; Billman 2011; Shaffer et al. 2014; Billman et al. 2015; Ernst 2017a, b) or as measures of training load, exercise response and performance (Aubert et al. 2003; Hottenrott et al. 2006; Bellenger et al. 2016b; Hottenrott and Hoos 2018; Michael et al. 2017; Lundstrom et al. 2023). These metrics may capture quite different HRV components, and their interpretation is always context-sensitive and depends on the application setting (for recent reviews, e.g., Sassi et al 2015; Shaffer and Ginsberg 2017, 2020).

Time-domain indices may be expressed in original units or as the natural logarithm (Ln) of original units to provide a more normal distribution (Shaffer and Ginsberg 2017). Frequency-domain indices are calculated as original units, as percentages of total spectrum, or as normalized units and estimate the distribution of absolute or relative power into four frequency bands, that are the ultra-low frequency (ULF), very-low frequency (VLF), low-frequency (LF), and high-frequency (HF) bands with different representation of autonomic/physiologic mechanisms (Task Force 1996; Shaffer and Ginsberg 2017). Non-linear indices may allow to quantify non-linear dynamics, complexity, and rather qualitative characteristics of HR time series, since the mechanisms involved in ANS regulation probably interact in a non-linear way (Goldberger 1990; Goldberger et al. 2002; Huikuri et al. 2009; Nicolini et al. 2012; de Godoy 2016). When capturing autonomic status through monitoring purposes, most commonly applied linear time- and frequency-domain HRV metrics display rather general descriptive statistical features or the distribution of the frequency content of the signal. For example, the standard deviation of all normal-to-normal R–R intervals over a given time interval (SDNN) is a general estimate of the global variability of the time series. In addition, the amount of efferent vagal modulation can be estimated from several parasympathetic-dominated HRV metrics across different domains of analysis like root mean square of successive differences of normal-to-normal R–R intervals (RMSSD), HF power, or standard deviation 1 (SD1) from the Poincaré Plot, while metrics from different recording durations may not be used interchangeably and their physiological meaning may vary considerably (Task Force 1996; Shaffer and Ginsberg 2017; Laborde et al. 2017; Gronwald et al. 2024). Further, selected metrics can be directly related to each other (e.g., RMSSD and SD1, Ciccone et al. 2017).

Although 24-h-HRV-recordings are used to represent the “gold standard” for clinical HRV assessment (Shaffer et al. 2014), short-term and ultra-short-term measurements with pre-stabilization periods are increasingly employed and validated for specific applied settings (Shaffer et al. 2020). In addition, it should be noted that for several HRV metrics, there is still an ongoing debate about their practical relevance and optimal recording lengths as these strongly depend on the algorithm and the setting. However, for a valid use of HRV in the fields of sports medicine and exercise science, careful considerations on standardized assessment, preprocessing, analysis, and context-sensitive interpretation are mandatory (Laborde et al. 2017; Gronwald et al. 2024; see section “Practical recommendation for implementation”).

Postural change as an autonomic challenge of interest

In applied settings of sports and exercise science, HRV has been assessed under various conditions, at rest (e.g., Schmitt et al. 2006; Plews et al. 2013a, b), in supine and standing positions (e.g., Schmitt et al. 2013; da Silva et al. 2015) or seated (e.g., Plews et al. 2017), during sleep (e.g., Pichot et al. 2000; Garet et al. 2004; Nuuttila et al. 2022), during exercise (e.g., Sandercock and Brodie 2006; Michael et al. 2017; Gronwald and Hoos 2020), or during the post-exercise recovery period (e.g., Buchheit et al. 2007; Seiler et al. 2007; Stanley et al. 2013; Hug et al. 2014) using different recording lengths. Originally, resting HR and/or HRV was recorded and interpreted in a standardized relaxed situation (e.g., lying in supine position first thing in the morning after waking up or during the entire night) as part of an assessment of resting physiology less influenced by external factors (Aubert et al. 2003; Buchheit et al. 2005). For the comparability of measurement results, body position is very important, as different body positions, including supine, sitting, and standing positions have a significant influence on HR and HRV metrics (Task Force 1996; Holmes et al. 2020; Pomeranz et al. 1985; Hnatkova et al. 2019). For example, the highest global HRV is usually measured in a supine position, while HRV decreases in the sitting position, and further in the standing position. However, to assess the health and physiological state of the organism, it might be more useful to look at how the global system responds to a challenge or provocation approach (Task Force 1996) such as physiological perturbations like cough, respiration, the Valsava maneuver, physical exercise, or postural change (Lipsitz et al. 1990; Freeman 2006).

Active standing up as “active stand test” is the most practical postural maneuver to challenge the cardiovascular autonomic function and has a long tradition in clinical medicine with standardized assessment and analysis for clinical practice (Freeman 2006; Freeman et al. 2011; Finucane et al. 2019). In addition, recent evidence shows that HRV profiles in supine and standing positions are associated with health and lifestyle markers and may reveal abnormalities undetected at only one of the two positions (Goncalves et al. 2015; Grosicki et al. 2022). This potentially affects measurement sensitivity according to lifestyle factors (Hynynen et al. 2011), and long-term risk stratification in healthy individuals (Carnethon et al. 2002; McCrory et al. 2016), which may reflect dysregulation of the parasympathetic branch of the ANS aiding clinical decision-making. In addition, it has been hypothesized that measurements taken while sitting are more strongly associated with changes in fitness level than measurements taken while lying down (Rabbani et al. 2021). Thus, a sitting or standing body position possibly implies an autonomic stressor of interest, with enhanced sensitivity compared to a measurement in supine position. For example, in the case of highly trained endurance athletes (especially with high volume of low-intensity aerobic training), despite high parasympathetic activity, this cannot be meaningfully represented via supine HRV analysis. This so-called "parasympathetic saturation" is reflected in a rather unchanged or not detectable change in vagally related HRV metrics despite a decreased HR (and increased R–R intervals) (Kiviniemi et al. 2006; Plews et al. 2013b; Buchheit 2014). Here, vagally related HRV metrics reflect the magnitude of modulation in parasympathetic outflow as opposed to overall parasympathetic tone (Hedman et al. 1995).

In line with the active stand test in clinical medicine, that provides additional information, and overcomes some of the aforementioned limitations, a combination of HRV analysis during both supine and standing position or an active orthostatic test has been proposed for training monitoring purposes and a reliable testing procedure with the potential of additional information about HR(V) reactivity and recovery (Bosquet et al. 2008; Grant et al. 2012; Schmitt et al. 2013, 2015a, b; Hottenrott and Hoos 2018; Laborde et al. 2017, 2018; Manser et al. 2021). This test explores the reactivities of the parasympathetic branch (withdrawal) and the sympathetic branch (excitation) of ANS in response to the position change (Taylor 1994). In this context, Schmitt et al. (2015a) argued that HRV values obtained only from supine position do not provide information about the preserved or altered ability of dynamic adjustment of the ANS. They also suggested that especially HR(V) changes between supine and standing position as an orthostatic response assessment could better inform about cardiovascular autonomic functioning and fatigue state and may therefore potentially further enlighten non-functional overreaching and chronic overtraining response processes (Schmitt et al. 2013, 2015a, b; Meeusen et al. 2013a, b).

Physiological background of orthostatic testing

Besides dynamic physical exercise, upright posture represents a physical stressor that requires full capabilities of the reflexes for the regulation of cardiovascular function (Rowell 1993; Freeman 2006; Stewart 2012). Therefore, the detection of specific changes in HR and HRV during orthostatic testing could be a potential source of information about overload and overtraining associated with acute and chronic responses in the organism. Within the clinical setting, orthostatic challenges and corresponding testing scenarios typically include the standardized change in body position, either passive in a so-called tilt test with individuals lying down on a table that can be tilted or as an active change from a lying or sitting position to an upright or standing position (e.g., active standing up; Freeman 2006; Sutton et al. 2021; van Zanten et al. 2024). This change challenges acute regulation responses by means of stress due to gravity within the ANS in general and the cardiovascular system in particular. Therefore, a normal hemodynamic response to orthostatic challenge is driven by and highly dependent on a sequence of multiple interrelated mechanisms, including several redundant feedback loops to counteract inadequacy of any one subsystem involved (Freeman 2006; Stewart 2012; Soloveva et al. 2020; see Fig. 1).

Gravitational forces due to orthostatic challenge shift approx. 400–800 ml of intra-vascular blood volume from the chest area into the splanchnic and pelvis compartment as well as into the buttock and leg vessels (Rowell 1993; Freeman 2006; Stewart et al. 2006; Stewart 2012; Soloveva et al. 2020). In addition, volume shifts out of the heart and the pulmonary vascular bed decrease the pressure of right ventricular filling with a subsequent reduction of cardiac output. In the follow-up due to decreased venous return (Sander-Jensen et al. 1986), blood pressure slightly decreases and HR increases. This cascade also triggers aortic (located in the walls of the large blood vessels, particularly in the aorta and the carotid sinus arteries) and carotid baroreceptor (located in the atria of the heart and in the blood vessels of the lungs) reflexes and stimulates brain ANS centers leading to sympathetic activation and vagal withdrawal accompanied by changes of plasma hormone concentrations (e.g., norepinephrine, epinephrine, vasopressin, angiotensin II; Sander-Jensen et al. 1986; Freeman 2006). This further stimulates compensatory vasoconstriction and HR increase (Ricci et al. 2015). Consequently, during an orthostatic challenge, autonomic regulatory processes strive to maintain blood pressure homeostasis (after short-term initial

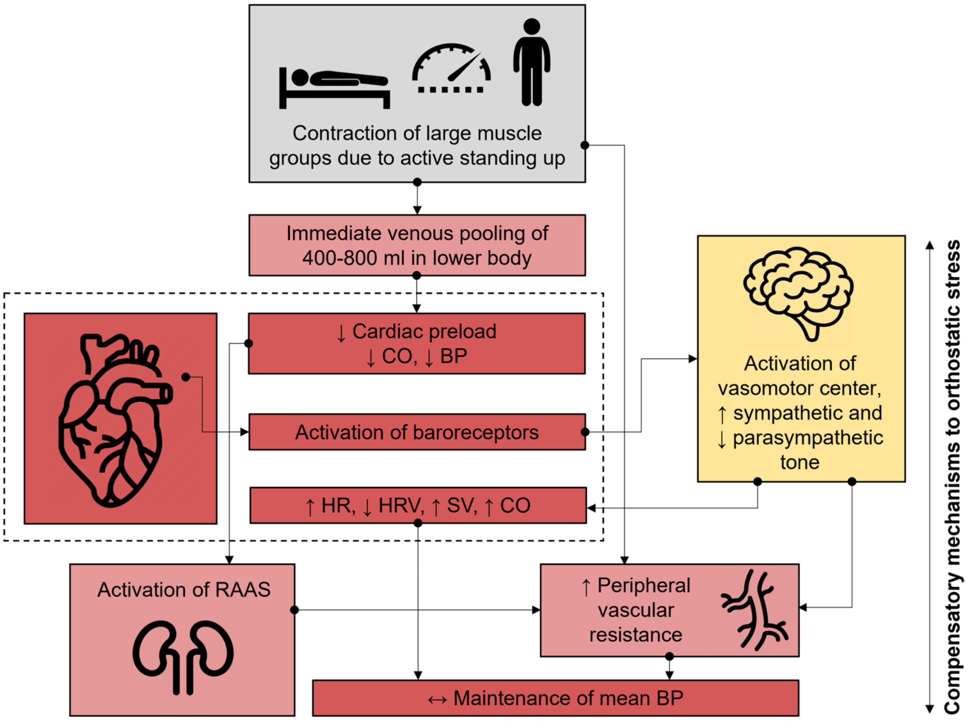

Fig. 1 Normal physiological and compensatory responses to active standing up modified from Soloveva et al. (2020) with information added from Rowell (1993) and Freeman (2006). *CO* cardiac output, *BP* blood pressure, *HR* heart rate, *HRV* heart rate variability, *SV* stroke volume, *RAAS* renin–angiotensin–aldosterone system

hypotension) and secure adequate hemodynamics to avoid cerebral hypoperfusion (Stewart 2012).

Beyond inter-individual variability, several pathophysiologic alterations in the cardiovascular responses to orthostatic challenges may occur, such as orthostatic hypotension, neurally mediated syncope and postural tachycardia syndrome (POTS) in all of which dysfunctional ANS-regulation, altered baroreflex sensitivity, and hypovolemia interact with other factors (e.g., genetics, aging, and postprandial status) and result in orthostatic intolerance (Freeman 2006; Barantke et al. 2008; Freeman et al. 2011; Stewart 2012; Swai et al. 2019; Soloveva et al. 2020). Furthermore, cardiovascular deconditioning and physical fitness were shown to interfere with normal orthostatic regulation, and the relationship with orthostatic intolerance was characterized as a shallow "U" shape, with a high incidence of orthostatic intolerance at both sides of the "fitness spectrum" (Levine 1993). This could be a potential limitation in the application of orthostatic testing, particularly for well-trained endurance athletes, and should be evaluated on an individual basis.

As a diagnostic tool for pathophysiologic alterations and the evaluation of physiologic reflex patterns, the application of position change from lying to standing was already introduced almost 50 years ago as a standardized test of autonomic function in diabetes (Ewing et al. 1978). As described before, the maneuver induces an integrated reflex response of the cardiovascular system, that trigger distinctive alterations in HR and blood pressure (Johnson and Spalding 1974; Ewing et al. 1978; Pomeranz et al. 1985). From a diagnostic perspective of the ANS, HR and HRV markers during passive tilt testing (e.g., Task Force 1996; Tulppo et al. 2001) typically indicate vagal withdrawal, and sympathetic excitation in a reciprocal fashion associated with an HR increase, a HF power decrease, and an increase in normalized LF power. In addition, increases in short-term correlation properties of HRV suggest reduced complexity in HR dynamics with the change to an upright body position, similar to low-intensity dynamic physical exercise (not detected by linear and other non-linear HRV metrics; Tulppo et al. 2001). However, passive tilt only entails a minimal engagement of central drive and muscular activity and is compatible with quite accurate stationary conditions (Malliani et al. 1991; Montano et al. 1994). These acute responses were reported in numerous studies and were mainly related to baroreflex activity and sensitivity (Tulppo et al. 2001; Montano et al. 1994; Nakamura et al. 1993; Butler et al. 1993, 1994). However, the exact responses (predominance of the cardiopulmonary or arterial baroreflex, predominance of norepinephrine or epinephrine, etc.) seem to be highly dependent on the specific protocol applied (e.g., mild vs. more pronounced tilt, velocity of inclination, and duration of the phases) and can differ substantially between different populations with direct effects on orthostatic tolerance (Mellingsæter et al. 2015; Sander-Jensen et al. 1986; Montano et al. 1994; Lipsitz et al. 1990; Butler et al. 1993; Levine 1993).

Contrary, active standing up produces different responses than a passive tilt test, adding information about changes occurring during actual tilting (Ewing et al. 1980). It is well documented that there is a transient fall in blood pressure while standing, with stimulation of the carotid baroreceptors and consequent reflex increase of HR and peripheral vasoconstriction in concert with cardio-postural interaction and skeletal muscle-pump activity (Johnson and Spalding 1974; Vinik et al. 2003; Xu et al. 2017). A reduction in blood pressure and initial hypotension occurs only during the initial transient mechanical disequilibrium. After that acute response systolic and diastolic blood pressures are usually slightly increased compared to supine lying body position (Stewart 2012). HR responses to standing have long been observed in healthy individuals (Hill 1895), while the immediate HR response has only been briefly documented at the beginning (Burke et al. 1977; Page and Watkins 1977). The ANS response to standing is reproducible and initiated by instantaneous cardiac vagal withdrawal followed soon after by sympathetic activation and vagal reactivation over the first 25–30 heartbeats. Thus, an increase of HR occurs immediately when standing up and HR will reach a peak after 15–20 beats and is less marked during passive tilting (Ewing et al. 1980; Vinik et al. 2003; Rooke and Sparks 2003), but the rebound only occurs with active orthostatic challenge, presumably due to the associated muscular activity of large muscle groups (Rowell 1993). Due to these observations, the 30:15 ratio was frequently used in clinical settings to assess physiological responses and cardiac vagal function during active standing up, which describes the ratio of HR increase at approx. 15 s after standing (the shortest R–R interval at or around the 15th beat) to the relative bradycardia that occurs at approx. 30 s after standing (the longest R–R interval at or around the 30th beat; Ewing et al. 1978, 1980). Due to variation in individual responses, an increase in sensitivity may be reached by enlarging the window of evaluation or measuring the ratio of the absolute maximum (peak HR) and minimum HR after standing up (Mitchell et al. 1983). Normal values for the 30:15 ratio were considered to range between 1.15 and 1.12 in 21–30-year-old individuals, 1.12 and 1.10 in 31–40-year-old individuals, 1.10 and 1.08 in 41–50-year-old individuals, and 1.08 and 1.07 in 51–60-year-old individuals (Ziegler et al. 1992; Freeman 2006).

Hence, early on, it has been recognized that sitting and standing, rather than lying (alone), should be considered as additional resting physiology postures (Gauer and Tiron 1965; Burke et al. 1977). In addition, in sport and exercise science, an orthostatic test usually requires active standing up, which leads to a higher degree of change in HR and blood pressure, and seems to be more sensitive and feasible for monitoring purposes in different fields of sports application (Hottenrott and Gronwald 2014; Hottenrott and Hoos 2018). Figure 2 displays the temporal course of the HR and R–R intervals during an orthostatic test with an active postural change from supine lying to standing. In that regard, Hynynen et al. (2011) confirmed earlier results, that life stress induces autonomic perturbations that could be assessed via orthostatic testing and might be helpful to improve individual load and recovery management. Also, Lucini et al. (2002) showed higher incidence of stress symptoms associated with lower HRV during the orthostatic test after awakening. This association was found during both supine rest and standing positions. These findings are in line with Porges (1992), who suggested that the parasympathetic nervous system acts as the general modulator of stress vulnerability and reactivity, which could be directly investigated via orthostatic testing. In the next section, we will discuss further data and specific responses during orthostatic testing in the applied field of exercise science and sports practice.

Orthostatic testing in exercise science and sports practice

In the last decades, several studies have shown the advantage of evaluating a standing position and the comparison between supine lying and standing (upright position) in response to active standing up (and tilting) in endurance and intermittent sports such as team sports (e.g., soccer). Here, prior studies reported additional sensitivity for the assessment of training status, performance level, and the dynamic adaptability of cardiac autonomic modulation (Gilder and Ramsbottom 2008; Rave and Fortrat 2016; Bellenger et al. 2016a; Maggioni et al. 2020), as well as for the reflection of fatigue states, parasympathetic hyperactivity, and overreaching (Uusitalo et al. 2000; Hedelin et al. 2000; Portier et al. 2001; Hynynen et al. 2008; Le Meur et al. 2013; Schmitt et al. 2013, 2015b; Bellenger et al. 2016a; Schneider et al. 2019; Barrero et al. 2020). In a conceptual framework for contextualizing HR measures for training and recovery prescription by Schneider et al. (2018), it is also summarized that the autonomic shift associated with an orthostatic challenge may be influenced by training-related phenomena, such as an overall vagal enhancement through low-intensity aerobic training, pre-competitive anxiety, overall stress (Hynynen et al. 2011), and fatigue phenomena from preceding exercise sessions or competition (Gratze et al. 2005; Schäfer et al. 2015), as well as overtraining (Hynynen et al. 2008). In a meta-analysis by Manresa-Rocamora et al. (2021), the authors concluded that resting vagal-related HRV indices measured in the standing position should be used to increase the sensitivity for parasympathetic hyperactivity in functionally overreached athletes. Measuring while standing might also

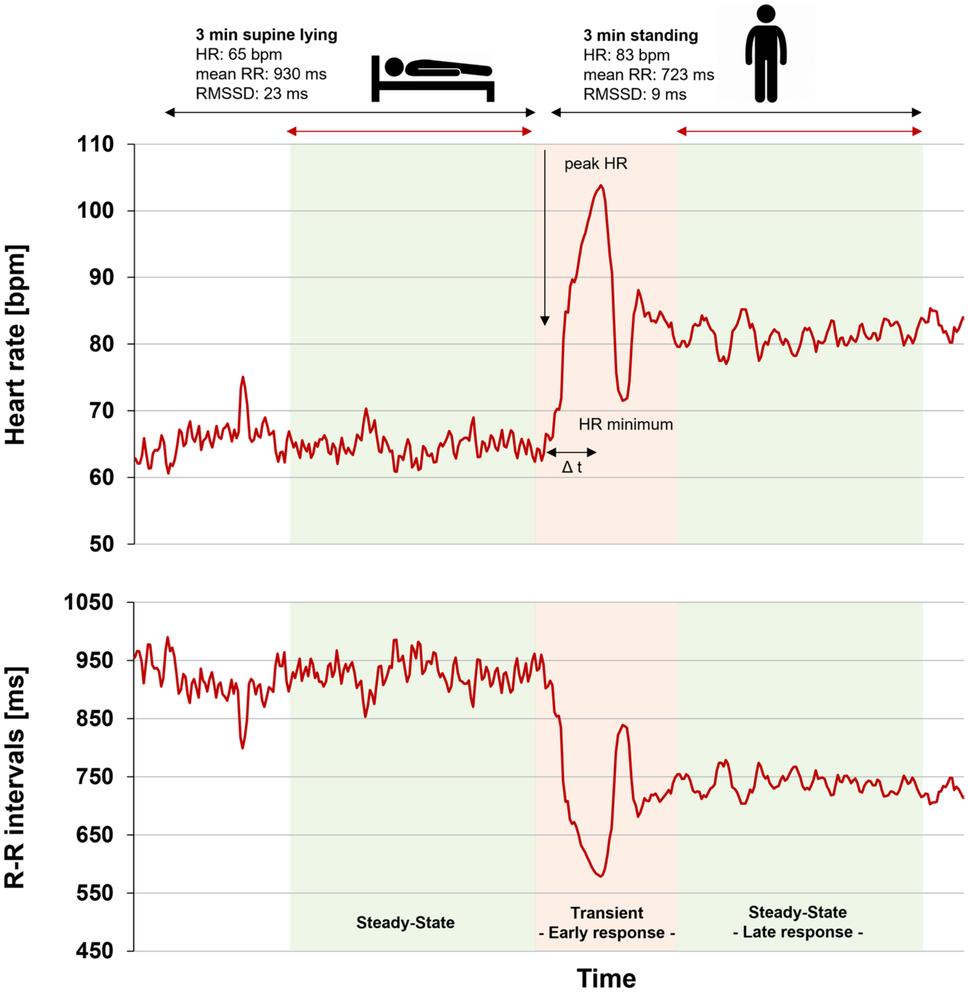

Fig. 2 Example of a heart rate (HR) and R–R interval profile of a 35-year-old healthy active individual without specific adaptation during an orthostatic test as part of a 3-min measurement while lying down in supine position, followed by a 3-min measurement while standing. The black vertical arrow indicates the change in body position due to active standing up and the compensatory transient reaction of the HR and R–R intervals (red shaded area). It is noticeable that the variability of the HR- / R–R-time series is much greater in the lying position compared to the standing position. Briefly, The compensatory reaction of the cardiovascular system leads to a peak HR of 103 beats per minute (Δ t: time to peak HR = 15 s) and an HR minimum of 72 beats per minute (Ratio = 1.43) before the time series stabilizes again—characterized by an increase in HR and both a reduction in the mean R–R interval and the RMSSD due to the change in body position. Green shaded areas display the 2-min steady-state windows of analysis during supine and standing position. From a qualitative perspective, the shape of the HR change after standing up shows a steep increase (in regard of the time to peak HR) and fast decrease which potentially stands for a good responsiveness and regulation quality

counteract the above described issue of parasympathetic saturation as a common phenomenon among healthy individuals (Goldberger et al. 2001; Kiviniemi et al. 2004, 2006), especially associated with low-resting HR in well-trained endurance athletes (Janssen et al. 1993; Buchheit et al. 2004; Kiviniemi et al. 2007). Other studies emphasize the implementation and analysis of the combination of body positions (Flatt & Esco 2015). This supports the association that an orthostatic stimulus may be more favorable than supine lying or sitting measurements alone to obtain specific information on the status of the cardiac autonomic regulation (Kiviniemi et al. 2007).

In that regard, Le Meur et al. (2013) evaluated alterations in autonomic function associated with functional overreaching in triathletes, showing how standing measurements could be used to detect parasympathetic hyperactivity compared to supine measures. In addition, Bellenger et al. (2016a) found that RMSSD assessed in a supine position was less sensitive in detecting potential parasympathetic hyperactivity in overreached endurance athletes after heavy training phases, and also according to improvements in performance level, suggesting that standing measures of HRV are more appropriate for detecting autonomic disturbances in the present context. However, the results of Bellenger et al. (2016a) demonstrate that increases in RMSSD due to specific training stimuli may be indicative of both positive and negative physiological responses. Therefore, additional measures such as psychometrical data are required to add context information for HR and HRV analysis interpretation (Le Meur et al. 2013; Tian et al. 2013; Buchheit 2014). In this regard, Hottenrott et al. (2021) published a case study assessing a viral infection in an elite marathon runner. In line with the general notion that an increase in resting HR and a decrease in RMSSD suggest a suppression of vagal activity (Buchheit 2014; Laborde et al. 2018), the viral infection had a direct influence on HR and HRV during orthostatic testing. An increase in HR was accompanied by a decrease in RMSSD in the standing position. Further, the kinetics of HR during position change was significantly different in the HR increase (time to peak HR) from a typical course in a healthy condition with a slower increase due to infection. Although there are no further findings in the literature according to these observations, reactivity of HR(V) is supposed to bear the potential of additional information in HR time series analysis due to associations of a resilient system (Scheffer et al. 2018; Laborde et al. 2017, 2018; Manser et al. 2021). Bellenger et al. (2016c, 2017) also found a slower maximal rate of HR increase at the onset of physical exercise (e.g., assessed via submaximal testing scenarios) in athletes suffering from exercise-induced fatigue due to overload training. Therefore, this measure could also be sensitive for different kinds of stressors including internal or external factors (Nelson et al. 2014, 2017; Bellenger et al. 2016b, c, 2017). A second main finding of Hottenrott et al. (2021) is that HR and HRV values changed more substantially in the standing position compared to supine position during viral infection. This was particularly pronounced in the RMSSD values. The findings of this report are limited to one case but could have some implications for sports practitioners and coaches looking to both ensure the health of their athletes, and for using HRV as a tool to monitor training processes and the return to sport after a viral infection.

Based on previous findings (Le Meur et al. 2013; Buchheit 2014; Plews et al. 2012, 2013b) and experiences in coaching elite athletes, Hottenrott and Hoos (2018) displayed schematic examples of HR and RMSSD-based HRV alterations during orthostatic testing and with associated functional states (e.g., acute and chronic fatigue, parasympathetic saturation) following different training characteristics (e.g., high-intensity training, high-volume training) compared to baseline assessments. It is mentioned that the average HR in the standing position of healthy individuals is on average 10–25 beats higher than the HR at rest in supine position, depending on age (Dambrink and Wieling 1987; van Wijnen et al. 2017). Standing also induces a three- to four-fold decrease of vagally related HRV indices compared to the supine position (Aubert et al. 2003; Hottenrott and Hoos 2018). It is also stated that there are specific and inter-individual variations in accordance to acute and chronic responses of life and physical training stressors. Main characteristics could be that high-intensity exercise over several days can lead to sympathetic overreaching, which is reflected by increased HR and decreased vagal activity in both supine and standing position (Hottenrott and Hoos 2018). Furthermore, high-volume training combined with some intensity peak sessions induce similar changes of supine lying values, whereas there could be a lower counter-regulatory response in the standing position. Consequently, the HR difference between supine and standing position is reduced (Hottenrott and Hoos 2018; Hynynen et al. 2008). Further, an attenuation of both parasympathetic and sympathetic activity during both supine and standing positions could be found in overtrained endurance athletes (Hynynen et al. 2008). The response to the standing position seemed to be lower than in non-overtrained athletes with the tendency of further decreased HRV in the standing position as a sign of pronounced vagal withdrawal and in some cases decreased sympathetic excitability associated with a potential overtraining state (Hynynen et al. 2008). In further studies of active orthostatic testing, it could be shown that the variation in HR and HRV indices comparing supine and standing positions is strongly correlated with the fatigue status in endurance athletes (Barrero et al. 2019). Therefore, the difference between standing and supine HR and HRV after active standing up could be a simple analysis option, e.g., with lower HR change between supine and standing positions indicating a potential maladaptive training status (Barrero et al. 2019, 2020). In addition, extensive high-volume training with low exercise intensity may lead to parasympathetic saturation, which could be indicated by a low HR and high HRV in both supine and standing position. Due to the high vagal activity, there is almost no HR difference between both body positions. Potentially, physiological states of functional overreaching and some kind of overtraining can be distinguished by the alteration of these functional states through changes in training characteristics (e.g., intensity, volume, and frequency). For example, parasympathetic saturation can be acutely counteracted with a reduction in training volume, introducing more intensity peaks in the following micro-cycle (Hottenrott and Hoos 2018). However, as a significant main characteristic, it could be noted that additional pathophysiological conditions consist in a reduced responsiveness or counter-regulation of neural drive in ANS according to an excitatory stimulus, such as an orthostatic challenge (Montano et al. 2009).

Practical recommendation for implementation

Regular testing is mandatory for appropriate data interpretation from resting physiology that includes orthostatic testing. Regular assessment can enhance understanding of how the organism responds to training load and other lifestyle factors that may interfere with ANS activity (e.g., work-life stress, sleep quality and duration, alcohol, nutrition, infection, environmental conditions, and changes such as temperature or altitude; Sandercock et al. 2005; Buchheit 2014; Fatisson et al. 2016). Regular testing should comprise at least three-to-four times a week in standardized conditions (e.g., same days in the micro-cycle, first thing in the morning after waking up) and testing frequency may be increased in periods of accumulated workload or overall stress (e.g., altitude and training camps, travel) (Buchheit 2014). To obtain reliable results, standardized conditions and application of recommended standards (e.g., Task Force 1996; Quintana & Heathers 2014; Sassi et al. 2015; Laborde et al. 2017) are mandatory to derive appropriate interpretations. To minimize stimuli affecting ANS function, the test should be performed in a quiet, dimly lit room at a comfortable temperature of around 21–23 °C (Finucane et al. 2019). Reliability of specific HRV measures can be dependent on body position (Sandercock et al. 2005; da Cruz et al. 2019; Cassirame et al. 2019; Holmes et al. 2020). In addition, the speed of standing up and the magnitude of active muscle contraction can be influencing factors due to cardio-postural interaction and muscle-pump activity (Kamiya et al. 2009; Xu et al. 2017). Therefore, it is recommended to stand up with a steady and comparable speed for multiple testing. Specifically, HR and HRV from orthostatic testing were shown to be reproducible both prior and after postural change in healthy participants and in patients with a history of acute coronary disease (Dantas et al. 2010; Schäfer et al. 2015; Vescovi et al. 2019). Recording conditions can be well replicated for morning measurements, which seem to be less susceptible to daily stressors and more representative of upcoming daily readiness (Nuuttila et al. 2022). Morning HR(V) measurements can also be implemented using low-cost and easy-to-use wearable technologies (e.g., smartphone-based applications), whereas orthostatic testing needs to be further evaluated with photoplethysmography measurement principles (PPG; e.g., smartwatch at the wrist, ring at the index finger) due to motion artifact susceptibility and the ability to sensitively detect the physiological changes and thus beat-to-beat intervals occurring during and after postural changes (Esco et al. 2017; Charlton et al. 2022). In that regard, further technical improvements of PPG measurement principles and wearable applications are necessary. Hence, currently HR(V) monitors enabling electrophysiological measurement principles (e.g., electrodes embedded in chest strap devices, electrode patches) with internal memory, or Bluetooth/ANT + coupled with e.g., smartwatches or smartphones are recommended for orthostatic testing.

A short guide to orthostatic testing with a chest strap device:

- Between waking up and recording, it is mandatory to use the bathroom (to empty bladder). In case you do not need to go to the bathroom, please simulate it.
- Fit on the chest strap with the sensor device. Moisten the electrodes of the strap and fasten it comfortable but ensure that it does not slip.
- There should be no disturbances around (e.g., talking people, television, music, and telephone noise).
- Lie back and find a comfortable supine position, then start recording.
- Be relaxed and calm. Keep your eyes open and try to breathe calmly and spontaneously. Avoid swallowing and yawning during the measurement.
- Both when measuring while lying down and during standing position, try to move as little as possible.
- After 3 min stand up with a steadily speed. Record another 3 min while standing. Remain in an upright position. The arms hang sideways next to the body, the knees are slightly bent, and the view is directed forward.
- After that stop the recording.
- Perform the test regularly in the same body positions and at the same time of day in the morning after awakening.
- Compare your measurement values to your own historical data baseline.

After lying down, a stabilization period should be applied (at least 1 min of baseline leading to a steady signal and settlement of respiratory rhythm). The test continues with 2 min of steady-state analysis window recording in lying position followed by actively standing up for a minute of transient early response and 2 min of steady-state analysis in standing position (1 + 2 min in each position for 6 min in total; Bourdillon et al. 2017; Hottenrott and Hoos 2018). This time frame is recommended for time-domain HRV analysis (e.g., RMSSD). Beyond time-domain indices, the implementation of spectral HRV analysis for the potential clustering of fatigue-related processes was proposed (Schmitt et al. 2015a), although the presence of higher sensitivity to breathing pattern might complicate data interpretation (Saboul et al. 2013). However, due to influences of breathing pattern on vagal-related HRV indices (Laborde et al. 2022; Ritz 2024; You et al. 2024), spontaneous breathing is required and no paced breathing is recommended. If frequency-domain parameters are considered, the test procedure should be slightly extended in each position (1 + 4 min in each position for 10 min in total; Bourdillon et al. 2017). An example for test execution and the following suggestions for quantitative and qualitative analysis of an orthostatic test are shown in Fig. 2.

Quantitative outcomes for time-domain metrics:

- HR and HRV (e.g., RMSSD) average for the last 2-min lying down
- Peak HR and time to peak HR (Δ t) after active standing up
- Ratio of peak HR and HR minimum after active standing up
- HR and HRV average for the last 2 min in standing position
- HR and HRV change between supine and standing positions (e.g., low HR change may reflect a maladaptive training status)
- Absolute sum of the HR and HRV change in supine and standing positions compared to the previous test (e.g., HR is 2 bpm higher in supine position and 4 bpm higher in standing position compared to the previous day leading to an overall difference of 6 bpm)

As a qualitative outcome the shape of the HR change after standing up could be evaluated (e.g., a steep increase and fast decrease potentially stands for fast response and good regulation quality; a slow increase and decrease stands potentially for fatigue processes and disturbed regulation pattern).

As mentioned earlier, Schmitt et al. (2015a, b) also proposed the implementation of spectral HRV analysis such as LF and HF for more sensitivity in fatigue detection and monitoring of the adaptive training-recovery process as opposed to the sole usage of time-domain HRV indices. One argument in favor of this is that RMSSD does not provide isolated information on the sympathetic-related modulation. Here, a decrease in RMSSD may lead to a biased interpretation due to parasympathetic saturation (Kiviniemi et al. 2004); this could be the result of a sympathetic overactivity combined with a saturation phenomenon (Schmitt et al. 2015a). However, a reductionistic simplification and assignment to parasympathetic and/or sympathetic regulation pattern only is also not justified by specific frequency domains. Here, inconsistent results are often generated using the LF/HF-frequency-domain ratio, and therefore, it should be discouraged to be used as a simple metric for sympatho-vagal balance (e.g., Billman 2013; Michael et al. 2017). Moreover, non-linear analysis of HRV such as the evaluation of short-term correlation properties of detrended fluctuation analysis (DFAa1) of HR time series has been shown to be more sensitive compared to the classical spectral and time-domain indices during postural change. Alterations in DFAa1 suggest reduced complexity in HR dynamics with an upright body position depending on inter-individual data history and may therefore be significant for specific organismic responses (de Souza et al. 2014; Tulppo et al. 2001). Further studies are necessary to evaluate the recommended outcomes in relation to other domains of analysis to ensure an integrated evaluation of the orthostatic response in the future.

Interpretation:There are specific and inter-individual differences in accordance with acute and chronic responses to orthostatic stress. Even if normative values for vagally related HRV metrics for resting conditions can be helpful on a statistical level to distinguish certain individuals on a population level (e.g., age, disease vs. no disease; sedentary vs. aerobically-trained), it is noticeable that there is still a large overlay of the actual data of compared populations (Huikuri et al. 2000; Aubert et al. 2003; Acharya et al. 2004; Zhang et al. 2020). Hence, an intra-individual regulation pattern as an individual profile should be primarily addressed and applied as the base of an interpretation together with further contextual data. Additional information from easily accessible psychometrical scales (e.g., Hooper-Index, Hooper et al. 1995) and other contextual information (e.g., training load analysis, performance test results) may overcome the lack of specificity in the interpretation of HR and HRV values, as these are strongly influenced by multiple factors (Sandercock et al. 2005; Buchheit 2014; Fatisson et al. 2016; Plews et al. 2012). As indicated by Schneider et al. (2018, 2019), it is recommended first to gain experience at an individual level through observation of data history to avoid inappropriate adjustments in exercise and training prescription due to overly simplistic training-response models. In addition, multiple studies and practical applications of HR and HRV trend analysis recommend the utilization of weekly HRV and rolling averages of a minimum of three-to-seven measurements as a baseline to be more sensitive compared to single-day values and to assess physiological alterations in vagal modulation and adaptation to training (Le Meur et al. 2013; Plews et al. 2013a, b, 2014; Flatt and Esco 2015; Medeiros et al. 2021). In addition, the use and interpretation of the coefficient of variation (CV) as the ratio of the standard deviation (SD) and the mean × 100 (%) of a data series and some kind of smallest worthwhile change (SWC) approach as a factor of ± CV or ± SD (implemented as a normal range) could be helpful for decision-support in load and recovery management (Plews et al. 2013a, b; Buchheit 2014; Gronwald et al. 2024). As an alternative, a fixed reference (average over multiple measurements) for the baseline of comparable phases of periodization or lifestyle could be used. This could be also applied to the different outcome measures of an orthostatic test (Polar Research and Technology 2024). All these information could be useful and relevant on an individual level, but their sensitivity should be evaluated in the applied field. In addition, these simple statistical implementations may help to increase the signal-to-noise ratio and the reproducibility of the applied measures improving quality and robustness of the monitoring process (Buchheit 2014; Schmitt et al. 2015a). Further, computational approaches with mathematical modeling are promising for quantifying ANS functionality reducing mathematical complexity and offering an easy-to-implement tool for clinical assessment and monitoring through innovative wearable technology (Wang et al. 2024).

Perspective and conclusion

In monitoring processes, physiological parameter interpretation is often difficult in isolation and/or with contrasting information involved. Therefore, a fine-tuned approach is recommended to implement several valid and practical tools, and to improve the effectiveness of monitoring practices when added to experts' knowledge (Boullosa et al. 2023). The ANS response to active standing up in orthostatic testing is initiated by instantaneous cardiac vagal withdrawal, followed by sympathetic activation and vagal reactivation. Generally, standing decreases vagally related HRV indices compared to the supine position. In overtrained endurance athletes, both parasympathetic and sympathetic activity are attenuated in supine and standing positions. The response to standing is lower than in non-overtrained athletes, with a tendency for further decreased HRV as a sign of pronounced vagal withdrawal and, in some cases, decreased sympathetic excitability. Therefore, the comparison of both body positions in a regular monitoring procedure could provide additional information and sensitivity about HR(V) reactivity and recovery due to health issues, fatigue processes, and overtraining phenomena. Measuring while standing might also counteract the issue of parasympathetic saturation as a common phenomenon especially in well-trained endurance athletes with low-resting HR (< 50 bpm). However, a likely increased incidence of orthostatic intolerance at both sides of the "fitness spectrum" should be evaluated on an individual level and must be taken into account when considering to implement orthostatic testing in specific subpopulations. Given the presented compilation of study findings, HR(V) analysis during orthostatic testing bears the potential to provide sensitive outcome measures about altered physiological conditions which should be interpreted within intra-individual data history in trend analysis and in regards of additional measures (e.g., psychometrical scales) to provide context for data interpretation. The effort involved should be considered in relation to the benefits for the specific field of application (e.g., sport-specific circumstances, individual situation after awakening). Thorough method comparison studies and systematic analysis of the literature must be conducted to further evaluate whether the use of regular orthostatic testing is able to offer an innovative, non-invasive, ecological valid, and time-efficient application to assess the health status and performance alterations of different populations, performance level, sport-specific demand profiles (modality and type of physical exercise), and could enhance decision-support for load and recovery management in exercise science and practice.

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