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A two-year examination of the relation between internal and external load and heart rate variability in Australian Rules Football

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ABSTRACT

The relationship between heart rate variability (HRV) and training load in team-sport is unknown. We therefore assessed relations between completed training-load in the previous 1-, 3- and 7-days and waking HRV in professional Australian Rules Football. Linear-mixed models analysed changes in HRV, considering training load from the previous 1-, 3- and 7-days. Total Distance (TD), distance >14.4 km · h−1 (HSR) and >24.9 km · h−1 (Sprint-Distance), duration >85% max heart rate and Rating of Perceived Exertion were included as independent variables. Sub-group analysis of season-phase and years of professional experience was also conducted. Increased three-day Sprint-Distance reduced HRV in the first 8-weeks of pre-season (−13.1 ms, $p = 0.03$) and across the data collection period (−3.75 ms, $p = 0.01$). In first-year players, higher previous-day (−63.3 ms, $p=0.04$) and seven-day TD (−38.2 ms, $p = 0.02$) reduced HRV, whilst higher seven-day HSR increased HRV (34.5 ms, $p = 0.01$). In players with five-to-seven years of professional experience, higher three-day (−14.4 ms, $p = 0.02$) and seven-day TD (−15.7 ms, $p = 0.01$) reduced HRV, while higher three-day HSR increased HRV (12.5 ms, $p = 0.04$). In players with greater than eight years of professional experience, higher previous-day Sprint-Distance reduced HRV (−13.1 ms, $p < 0.008$). Completed training load across the previous 7-days influences HRV, but the relation between variables is complex and influenced by professional experience and season-phase.

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Introduction

The monitoring of athlete training load is an integral practice within professional team-sport (Bartlett et al., 2017; F. O'Connor et al., 2019; F. K. O'Connor et al., 2020). The advent of global positioning systems (GPS) has enabled sports science practitioners to accurately quantify the external load completed by individual athletes in each training session or game (Bartlett et al., 2017; F. O'Connor et al., 2019; F. K. O'Connor et al., 2020). Further, the integration of GPS-derived external load with subjective (rating of perceived exertion) and objective (heart rate) internal load measures provides sports science practitioners with detailed insights into the physiological and psychometric stimulus of both training and competition (Bartlett et al., 2017).

Conversely, to capture the recovery response to training and/or competition (i.e., 24–72-h post) practitioners often use subjective wellness questionnaires (Gallo et al., 2017) neuromuscular fatigue monitoring techniques (Cormack et al., 2013) and in some cases salivary or blood markers (i.e., cortisol (Maso et al., 2004) and creatine kinase (Berriel et al., 2020)). While these methods provide meaningful insights, they are not without limitation, making their implementation problematic in professional team-sport environments. For example, athlete-specific psychometric questionnaires can be lengthy and repetitive in nature (Kellmann, 2002) which leads to challenges with compliance (Gallo et al., 2017) and many athletes choose to report data dishonestly due to a myriad of reasons (Coventry et al., 2023). Further, neuromuscular fatigue monitoring can be time consuming to implement within large cohorts, and saliva and blood markers can be highly variable and inconsistent (Baird et al., 2012; Nunes & Macedo, 2013). Accordingly, emerging technologies have led to novel recovery monitoring techniques within the field (Hornsby et al., 2022) with one such technique being the monitoring of heart rate variability (HRV). Indeed, while not without limitations (e.g., complications in deciphering practically meaningful changes from day-to-day variation (Buchheit, 2014)), the accurate quantification of internal load measures (i.e., HRV) in response to a given external load has direct implications for the optimisation of training load within specific training blocks and throughout competitive periods (Buchheit, 2014).

Heart rate variability reflects cardiac modulation by the sympathetic and vagal components of the autonomic nervous system, whereby the monitoring of HRV offers a non-invasive way to assess the balance between sympathetic and parasympathetic autonomic nervous system activity (Yugar et al., 2023). In periods of high stress, activation of the sympathetic nervous system increases heart rate and decreases HRV, whereas in periods of recovery, parasympathetic activity decreases heart rate and increases HRV (Berntson et al., 1997). As a result of the ability of HRV to provide non-invasive estimates of the balance

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between stress (sympathetic activity) and recovery (parasympathetic), HRV monitoring has emerged as a tool to monitor training and recovery adaptations in sport (Dong, 2016). Thus, the accurate recording of HRV may provide sports scientists and coaches with a means to evaluate autonomic function in response to an imposed training load, where increases in HRV measures have been shown to be related to positive training adaptations (Plews et al., 2013), and conversely reductions in HRV measures have been related to increased stress responses, recovery status (Buchheit, 2014) and overall health and well-being (Flatt & Howells, 2019; Flatt et al., 2019). Indeed, short-term (i.e., one-week to four-months) observations have shown HRV to be sensitive to fluctuations in team-sport training load (Buchheit et al., 2011; Chen et al., 2021; Flatt & Esco, 2015; Flatt & Howells, 2019; Flatt et al., 2019, 2020; González-Fimbres et al., 2021; Lechner et al., 2023; Lukonaitienė et al., 2020, 2021; Muñoz-López & Naranjo-Orellana, 2020; Muñoz-López et al., 2021; Naranjo et al., 2015; Nakamura et al., 2023; Piedra et al., 2021; Rabbani et al., 2019; Sánchez-Sánchez et al., 2021; Thorpe et al., 2015; Villafaina et al., 2022) with recent advancements in smartphone-based photoplethysmography (PPG) technology emerging as a practical means of quantifying HRV in the field (Holmes et al., 2020). This is simply done by placing the fingertip of the index finger over a smartphone camera lens (Plews et al., 2017) or by utilising a specifically designed fingertip optical pulse sensor (Holmes et al., 2020; Heathers, 2013). Accordingly, the recording of PPG HRV via smartphone applications presents a simple-to-use, non-invasive technology whereby volumetric variations in fingertip blood circulation are quantified (Castaneda et al., 2018). This method has been shown to have acceptable agreement with electrocardiogram-derived HRV (technical error of estimate 3.8%) (Heathers, 2013; Plews et al., 2017) and is related to changes in subjective training intensity in general population settings (Altini & Plews, 2021) and in response to short-term autonomic nervous system changes following resistance exercise (Holmes et al., 2020).

To the best of our knowledge, only one study has directly assessed the utilisation of fingertip waking PPG HRV monitoring in a team-sport environment. However, this study assessed the relation between environmental conditions and training and recovery variables (F. K. O'Connor et al., 2020) and not the relation between training load and changes in HRV. Nonetheless, the authors reported a reduction in a common measure of HRV (root mean sum of the squared differences between each successive heart beat [rMSSD]) 48 h post-training when training was undertaken when exposed to high levels of solar radiation (F. K. O'Connor et al., 2020). Of note, high solar radiation exposure was also associated with significant reductions in external training load, despite no changes in perceived exertion. This may indicate that the autonomic stress response for a given external workload is exacerbated when exposed to increasingly challenging environmental conditions; however, this notion remains unresolved and required further investigation. Nonetheless, it appears likely that waking fingertip PPG HRV monitoring presents as a simple to administer monitoring tool that is of benefit to practitioners in the field to manage fatigue and recovery in team-sport settings. However, the utility of smartphone derived PPG HRV to assess the physiological response to exercise in a large-scale longitudinal study in team-sport environments has not been assessed. To address this critical knowledge gap, the aim of this study was to evaluate relationships between internal and external training load and waking HRV, as assessed via photoplethysmography, across a two-season period in an elite team-sport setting (Australian Rules Football [ARF]). We hypothesised that periods of increased training load would be followed by decrements in waking HRV, and this effect would be magnified when higher training loads were completed over the previous 3- and 7-day periods.

Materials and methods

Participants

Forty-six professional male athletes (mean ± standard deviation [SD]); age: 26 [3] years, height: 190 [8] cm, body mass: 89.5 [9.8] kg, maximal aerobic speed 17.6 [0.8] km · h^{-1}, from one ARF club participated in this study. As we recruited a professional ARF team, the sample was limited to the number of professional players contracted to the ARF team across the two-seasons of the data collection period. Individual athlete years of experience within the professional ARF system was categorised for each season in the data collection period, for use as a covariate in statistical analyses. For individual data to be included within the analysis, participants had to have completed a minimum of three waking HRV recordings in the previous 7-days.

Experimental protocol

Internal and external training loads were captured across an 18-month period that comprised two pre-season periods and two in-season periods. A total of 5338 waking rMSSD recordings (111 [72] per player) and 7082 training and game observations (144 [80] per player) were included in the final analysis. To facilitate sub-group analyses, players were grouped according to their years of experience within the professional ARF system, as having one, two-to-four, five-to-seven or greater than eight years of professional experience. Data were grouped for each separate season, resulting in some observations for a single player being classified separately in Season 1 and Season 2 (accounted for within statistical analyses approach).

External load monitoring

External training and competition loads were captured via global position systems (GPS) for each participant and downloaded in accordance with previous methods (Bartlett et al., 2017). Participants used the same valid and reliable (coefficient of variation <5%) GPS device (S5, Catapult Sports, Melbourne, Australia) for each session to mitigate inter-unit measurement errors (Coutts & Duffield, 2010). Total distance and distance at velocities greater than 14.4 km·h^{-1} (High-Speed Running [HSR]) and 24.9 km·h^{-1} (Sprint Distance) (F. O'Connor et al., 2019) were analysed. Individual Total Distance, HSR and Sprint Distance were summated over 1-, 3- and 7-day periods.

Internal load monitoring

Within-training Heart Rate (HR) data was collected via chest strap HR monitors (T34, Polar Electro, Espoo, Finland). HR data was analysed by quantifying the total training duration where HR was greater than 85% of an individual's HR maximum. Maximum heart rate was ascertained by quantifying the highest heart rate achieved within training or games, when a new maximum heart rate was achieved, this was recorded and heart rate percentile zones were recalculated. Ratings of perceived exertion (RPE) was obtained 10–30 min following the completion of each training session using Borg's CR-10 scale (Borg, 1982). RPE was multiplied by session duration to obtain session-RPE training load (sRPE) (Foster et al., 2001). Individual HR data and sRPE were summated over 1-, 3- and 7-day periods.

Monitoring internal recovery

Objective measures of heart-rate variability (HRV) were assessed upon waking each morning by R-R series recording via photoplethysmography using a valid and reliable, commercially available smartphone application (HRV4Training) (Plews et al., 2017). Data was included within the analysis if it was deemed "optimal" by the smartphone application software (less than 6% artefacts) (Plews et al., 2017). Waking HRV data was subsequently analysed for the root mean sum of the squared differences (rMSSD) between each successive heartbeat, and compared to baseline data obtained from a rolling average of the prior 7-days. As a result of the complexities of HRV monitoring (Buchheit, 2014) especially when considering the known "bell-shaped" HRV response to training witnessed within elite endurance athlete cohorts (Buchheit, 2014) where cardiac autonomic regulation improves as "fitness" is acquired and then decreases as more intense training is completed (Buchheit, 2014) it was deemed appropriate to analyse data over 1-, 3- and 7-day time frames. Moreover, rMSSD was chosen as the HRV variable of interest due to the relationship with vagal activity (Malik et al., 1996) and greater reliability compared to other spectral indices (Al Haddad et al., 2011).

Statistical analyses

Intraindividual weekly coefficient of variation (CV) in rMSSD was calculated as the standard deviation divided by the mean multiplied by 100[20] to determine whether fluctuations in training load lead to variation in rMSSD across the training week. To explore how training load may influence waking HRV, linear mixed models were applied to internal and external load variables incorporating the individual as a random effect in *R* (v.4.2.2). The outcome variable of interest was the change in waking HRV from the previous 7-day mean, with training load metrics (Total Distance, HSR, sRPE and total training duration where HR was greater than 85% of an individual's HR maximum) included as fixed effects. A random intercept for each participant was included to account for repeated observations. Data were analysed across the whole experimental period and within pre-season (pre-season phase one [PS1], pre-season phase two [PS2]) and in-season (in-season phase one [IS1], in-season phase two [IS2], in-season phase three [IS3]) (Juhari et al., 2018) periods. Additional sub-group analysis was undertaken whereby years of professional ARF experience was accounted for within the analysis. These groups were defined as players with one, two-to-four, five-to-seven and greater than eight years of professional experience. The adequacy of the model structures was determined via visual inspection of diagnostic plots of the homoskedasticity and normality of residuals (fixed and random effects) and quantified using standard measures of intraclass correlations and coefficients of determination. Variables are reported using standardised regression coefficients (β), allowing assessment of practical significance where the β for each variable was multiplied by the standard deviation of change in dependent variable to obtain the absolute change in the units of measurement (Nieminen et al., 2013). $p < 0.05$ was deemed to be a statistically significant difference.

Results

Weekly coefficient of variation in rMSSD was not associated with the cumulative sum of any load variable in a given week (all $p > 0.05$).

Associations between HRV and training load in the previous 1-, 3- and 7-days across the entire collection period

An increase in cumulative Sprint Distance over a three-day period was associated with a reduction in waking rMSSD (−3.75 ms [CI = −0.6 to −6.3 ms], β = −0.06, $p = 0.01$). No further relations were evident between recorded load measures in the previous 1-, 3- and 7-days and a change in waking rMSSD at any time point within group-level analysis (all $p > 0.05$, Table 1).

Associations between HRV and training load within specific season phases

During PS1, an increase in Sprint Distance over a three-day period was associated with a decrease in waking rMSSD (−13.1 ms [CI = −0.7 to −24.6 ms], β = −0.17, $p = 0.03$). No further relationships were evident between recorded load measures and a change in waking rMSSD at any time point during the season (all $p > 0.05$).

Associations between HRV and training load as a factor of years of professional ARF experience

In players with one year of professional ARF experience, an increase in Total Distance completed on the previous day was associated with a reduction in waking rMSSD (−63.3 ms [CI = −1.25 to −125 ms], β = −1.01, Table 2, $p = 0.04$). An increase in cumulative seven-day Total Distance was associated with a decrease in waking rMSSD (−38.2 ms [CI = −69.5 to −7.52 ms], β = −0.61, $p = 0.02$). However, an increase in cumulative HSR across the previous seven-days was associated with an increase in waking rMSSD (34.5 ms [CI = 7.52 to 60.8 ms], β = 0.55, $p = 0.01$). No other training load variable was associated with waking rMSSD at any time point in players with one year of professional ARF experience (all $p > 0.05$). For players with two-to-four years of professional

Table 1. Associations between completed and change in rMSSD from seven-day mean across the entire playing squad.

	Predictors	std. Beta	std. CI (95%)	Δ rMSSD (ms)	95% CI (ms)	p-value
One-Day Cumulative Load	(Intercept)	0.00	−0.06 – 0.07	0.00	−3.76 – 4.38	0.88
	Total Distance	−0.07	−0.26 – 0.11	−4.38	−16.3 – 6.89	0.43
	HSR	0.12	−0.00 – 0.23	7.52	−0.00 – 14.4	0.05
	Sprint Distance	−0.03	−0.10 – 0.03	−1.88	−6.26 – 0.03	0.32
	sRPE	−0.05	−0.18 – 0.09	−3.13	−11.3 – 5.64	0.51
	Duration >85% HRmax	−0.02	−0.09 – 0.06	−1.25	−5.64 – 3.76	0.66
Three-day cumulative Load	(Intercept)	−0.00	−0.04 – 0.04	−0.00	−2.51 – 2.51	0.45
	Total Distance	−0.05	−0.16 – 0.06	−3.13	−10.0 – 3.76	0.36
	HSR	0.07	−0.03 – 0.17	4.38	−1.88 – 10.6	0.17
	Sprint Distance	−0.06	−0.10 – −0.01	−3.76	−6.26 – −0.63	0.01*
	sRPE	−0.01	−0.07 – 0.05	−0.63	−4.38 – 3.13	0.77
	Duration >85% HRmax	−0.02	−0.07 – 0.03	−1.25	−4.38 – 1.88	0.36
Seven-day Cumulative Load	(Intercept)	−0.00	−0.04 – 0.04	−0.00	−2.51 – 2.51	0.18
	Total Distance	−0.06	−0.17 – 0.05	−3.76	−10.6 – 3.13	0.28
	HSR	0.04	−0.07 – 0.14	2.51	−4.38 – 8.77	0.49
	Sprint Distance	−0.03	−0.08 – 0.01	−1.88	−5.01 – 0.63	0.18
	sRPE	0.00	−0.06 – 0.07	0.00	−3.76 – 4.38	0.95
	Duration >85% HRmax	−0.01	−0.06 – 0.04	−0.63	−3.76 – 2.51	0.78

std. Beta: standardised regression coefficient (beta), Δ rMSSD: change in root mean sum of the squared differences between each successive heart-beat, ms: milliseconds, 95% CI, 95% confidence interval, HSR: distance completed at velocities greater than 14.4 km·h-1, Sprint Distance: distance completed at velocities greater than 24.9 km·h-1, *: $p < 0.05$.

Table 2. Players with one year of professional ARF experience: association between completed load and change in rMSSD from seven-day mean.

	Predictors	std. Beta	std. CI (95%)	Δ rMSSD (ms)	95% CI (ms)	p-value
One-Day Cumulative Load	(Intercept)	0	−0.26 – 0.27	0.00	−16.3 – 16.9	0.48
	Total Distance	−1.01	−2.00 – −0.02	−63.3	−125 – −1.25	0.04*
	HSR	0.44	−0.00 – 0.89	27.6	0.00 – 55.7	0.05
	Sprint Distance	−0.01	−0.27 – 0.26	−0.63	−0.27 – 0.26	0.94
	sRPE	0.58	−0.19 – 1.36	36.3	−11.9 – 85.2	−0.14
	Duration >85% HRmax	0.20	−0.12 – 0.53	12.5	−7.52 – 33.2	0.22
Three-day cumulative Load	(Intercept)	−0.40	−0.17 – 0.17	−25.1	−10.6 – 10.6	0.95
	Total Distance	0.29	−0.85 – 0.05	18.2	−53.2 – 3.13	0.08
	HSR	0.02	−0.13 – 0.71	1.25	−8.14 – 44.5	0.17
	Sprint Distance	0.17	−0.18 – 0.22	10.6	−11.3 – 13.8	0.84
	sRPE	−0.04	−0.10 – 0.44	−2.51	−6.26 – 27.6	0.21
	Duration >85% HRmax	−0.40	−0.27 – 0.20	−25.1	−16.9 – 12.5	0.75
Seven-day Cumulative Load	(Intercept)	0.02	−0.17 – 0.20	1.25	−10.6 – 12.5	0.65
	Total Distance	−0.61	−1.11 – −0.12	−38.2	−69.5 – −7.52	0.02*
	HSR	0.55	0.12 – 0.97	34.5	7.52 – 60.8	0.01*
	Sprint Distance	−0.03	−0.21 – 0.15	−1.88	−13.2 – 9.39	0.77
	sRPE	0.10	−0.18 – 0.37	6.26	−11.3 – 23.2	0.49
	Duration >85% HRmax	−0.01	−0.25 – 0.23	−0.63	−15.6 – 14.4	0.93

std. Beta: standardised regression coefficient (beta), Δ rMSSD: change in root mean sum of the squared differences between each successive heart-beat, ms: milliseconds, 95% CI, 95% confidence interval, HSR: distance completed at velocities greater than 14.4 km·h-1, Sprint Distance: distance completed at velocities greater than 24.9 km·h-1, *: $p < 0.05$.

ARF experience, no load measures were associated with changes in waking rMSSD in (Table 3, all $p > 0.05$). For players with five-to-seven years of professional ARF experience, an increase in cumulative Total Distance over the previous three-days was associated with a reduction in waking rMSSD (−14.4 ms [CI = −1.88 to −2.6 ms], β = −0.23, Table 4, $p = 0.02$), but an increase in HSR completed during the previous three-days was associated with an increase in waking rMSSD (12.5 ms [CI = −0.63 to 24.4 ms], β = 0.20, $p = 0.04$). Moreover, an increase in Total Distance across the previous seven-days was associated with a reduction in waking rMSSD (−15.7 ms [CI = −3.76 to −28.2 ms], β = −0.25, $p = 0.01$). No other load variable was associated with changes in waking rMSSD in players with five-to-seven years of professional ARF experience (all $p > 0.05$). For players with greater than eight years of professional ARF experience, an increase in previous day Sprint Distance was associated with a reduction in waking rMSSD (−13.1 ms [CI = −3.76 to −23.2 ms], β = −0.21, Table 5, $p = <0.008$); no other load variable was associated with waking rMSSD (all $p > 0.05$).

Discussion

This study aimed to determine the relation between frequently utilised measures of training and competition load and waking heart rate variability as assessed by a commercially available smartphone application in a professional team-sport setting across a two-year period. On a group level, these data show that an increase in cumulative 3-day distance completed at velocities greater than 24.9 km·h^{-1} was associated with a decrease in waking HRV. Moreover, the magnitude of this effect was increased during pre-season phase one (i.e., the first 8-weeks of pre-season preparation), even when accounting for the years of experience within the professional ARF system.

Table 3. Players with two-to-four years of professional ARF experience: association between completed load and change in rMSSD from seven-day mean.

	Predictors	std. Beta	std. CI (95%)	Δ rMSSD (ms)	95% CI (ms)	p-value
One-Day Cumulative Load	(Intercept)	0.00	−0.11 – 0.12	0.00	−6.89 – 7.52	0.83
	Total Distance	−0.09	−0.44 – 0.25	−5.64	−27.6 – 15.7	0.58
	HSR	0.17	−0.03 – 0.38	10.6	−1.88 – 23.8	0.10
	Sprint Distance	−0.04	−0.14 – 0.06	−2.51	−8.77 – 3.76	0.45
	sRPE	−0.05	−0.29 – 0.19	−3.13	−18.2 – 11.9	0.69
	Duration >85% HRmax	−0.07	−0.20 – 0.05	−4.38	−12.5 – 3.13	0.25
Three-day cumulative Load	(Intercept)	0.00	−0.08 – 0.08	0.00	−5.01 – 5.01	0.11
	Total Distance	0.12	−0.06 – 0.30	7.52	−3.76 – 18.8	0.18
	HSR	−0.06	−0.24 – 0.11	−3.76	−15.0 – 6.89	0.48
	Sprint Distance	−0.08	−0.17 – 0.01	−5.01	−10.6 – 0.63	0.07
	sRPE	−0.05	−0.16 – 0.06	−3.13	−10.0 – 3.76	0.35
	Duration >85% HRmax	0.04	−0.06 – 0.13	2.51	−3.76 – 8.14	0.42
Seven-day Cumulative Load	(Intercept)	−0.01	−0.10 – 0.07	−0.63	−6.26 – 4.38	0.95
	Total Distance	0.07	−0.10 – 0.25	4.38	−6.26 – 15.7	0.41
	HSR	−0.16	−0.34 – 0.02	−10.0	−21.3 – 1.25	0.08
	Sprint Distance	−0.01	−0.10 – 0.07	−0.63	−6.26 – 4.38	0.72
	sRPE	0.01	−0.11 – 0.12	0.63	−6.89 – 7.52	0.91
	Duration >85% HRmax	0.03	−0.07 – 0.13	1.88	−4.38 – 8.14	0.55

std. Beta: standardised regression coefficient (beta), Δ rMSSD: change in root mean sum of the squared differences between each successive heart-beat, ms: milliseconds, 95% CI, 95% confidence interval, HSR: distance completed at velocities greater than 14.4 km·h-1, Sprint Distance: distance completed at velocities greater than 24.9 km·h-1, *: $p < 0.05$.

Table 4. Players with five-to-seven years of professional ARF experience: association between completed load and change in rMSSD from seven-day mean.

	Predictors	std. Beta	std. CI (95%)	Δ rMSSD (ms)	95% CI (ms)	p-value
One-Day Cumulative Load	(Intercept)	0.00	−0.11 – 0.11	0.00	−6.89 – 6.89	0.98
	Total Distance	0.04	−0.23 – 0.32	2.51	−14.4 – 20.0	0.76
	HSR	−0.04	−0.24 – 0.15	2.51	−15.0 – 9.39	0.66
	Sprint Distance	0.06	−0.06 – 0.18	3.76	−3.76 – 11.3	0.31
	sRPE	−0.10	−0.31 – 0.10	−6.26	−19.4 – 6.26	0.33
	Duration >85% HRmax	−0.01	−0.14 – 0.13	−0.63	−8.77 – 8.14	0.90
Three-day cumulative Load	(Intercept)	0.00	−0.11 – 0.11	0.00	−6.89 – 6.89	0.09
	Total Distance	−0.23	−0.44 – −0.03	−14.4	−27.6 – −1.88	0.02*
	HSR	0.20	0.01 – 0.39	12.5	0.63 – 24.4	0.04*
	Sprint Distance	−0.06	−0.16 – 0.05	−3.76	−10.0 – 3.13	0.31
	sRPE	−0.06	−0.19 – 0.06	−3.76	−11.9 – 3.76	0.32
	Duration >85% HRmax	0.03	−0.08 – 0.15	1.88	−5.01 – 9.39	0.58
Seven-day Cumulative Load	(Intercept)	0.00	−0.07 – 0.07	0.00	−4.38 – 4.38	<0.001
	Total Distance	−0.25	−0.45 – −0.06	−15.7	−28.2 – −3.76	0.01*
	HSR	0.16	−0.02 – 0.34	10.0	−1.25 – 21.3	0.08
	Sprint Distance	−0.03	−0.11 – 0.06	−1.88	−6.89 – 3.76	0.52
	sRPE	−0.08	−0.20 – 0.04	−5.01	−12.5 – 2.51	0.20
	Duration >85% HRmax	0.00	−0.10 – 0.10	0.00	−6.26 – 6.26	0.97

std. Beta: standardised regression coefficient (beta), Δ rMSSD: change in root mean sum of the squared differences between each successive heart-beat, ms: milliseconds, 95% CI, 95% confidence interval, HSR: distance completed at velocities greater than 14.4 km·h-1, Sprint Distance: distance completed at velocities greater than 24.9 km·h-1, *: $p < 0.05$.

Table 5. Players with greater than eight years of professional ARF experience: association between completed load and change in rMSSD from seven-day mean.

	Predictors	std. Beta	std. CI (95%)	Δ rMSSD (ms)	95% CI (ms)	p-value
One-Day Cumulative Load	(Intercept)	0.00	−0.13 – 0.13	0.00	−0.13 – 0.13	0.57
	Total Distance	0.06	−0.39 – 0.51	3.76	−24.4 – 31.9	0.78
	HSR	0.23	−0.03 – 0.49	14.4	−1.88 – 30.7	0.08
	Sprint Distance	−0.21	−0.37 – −0.06	−13.1	−23.2 – −3.76	0.008*
	sRPE	−0.12	−0.46 – 0.22	−7.52	−28.8 – 13.8	0.49
	Duration >85% HRmax	−0.05	−0.21 – 0.11	−3.13	−13.2 – 6.89	0.52
Three-day cumulative Load	(Intercept)	0.00	−0.12 – 0.12	0.00	−7.52 – 7.52	0.50
	Total Distance	0.00	−0.27 – 0.28	0.00	−16.9 – 17.5	0.97
	HSR	0.14	−0.11 – 0.38	8.77	−6.89 – 23.8	0.27
	Sprint Distance	−0.07	−0.21 – 0.07	−4.38	−13.2 – 4.38	0.35
	sRPE	−0.04	−0.23 – 0.15	−2.51	−14.4 – 9.39	0.69
	Duration >85% HRmax	−0.04	−0.18 – 0.10	−2.51	−11.3 – 6.26	0.56
Seven-day Cumulative Load	(Intercept)	0.00	−0.10 – 0.10	0.00	−6.26 – 6.26	0.05
	Total Distance	0.01	−0.26 – 0.27	0.63	−16.3 – 16.3	0.97
	HSR	0.17	−0.08 – 0.42	10.7	−5.01 – 26.3	0.18
	Sprint Distance	−0.12	−0.24 – 0.01	−7.52	−15.0 – 0.63	0.06
	sRPE	0.02	−0.17 – 0.21	1.25	−10.6 – 13.2	0.86
	Duration >85% HRmax	−0.01	−0.13 – 0.11	−0.63	−8.14 – 6.89	0.90

std. Beta: standardised regression coefficient (beta), Δ rMSSD: change in root mean sum of the squared differences between each successive heart-beat, ms: milliseconds, 95% CI, 95% confidence interval, HSR: distance completed at velocities greater than 14.4 km·h-1, Sprint Distance: distance completed at velocities greater than 24.9 km·h-1, *: $p < 0.05$.

Furthermore, there was a general trend for increasing Total Distance specified across multiple time frames over the previous week to be associated with a reduction in waking rMSSD, and for an increase in HSR to be associated with an increase in waking rMSSD. However, there were no relationships between standard measures of internal load monitoring, and associated changes in waking heart rate variability. Together, we highlight the complexity of training and competition load monitoring in team-sport and raise awareness that changes in load in a professional team-sport environment appear to exert measurable changes on the autonomic nervous system.

A consistent finding of our analysis was that an increased accumulation of sprint distance over the previous three days was associated with a reduction in waking rMSSD. This relationship was evidenced across the two-year data collection period as well as within specific season phases (at the commencement of the pre-season preparation period). Further, reductions in the change in waking rMSSD were evident in response to increased sprint distance over the previous three days in players with greater than eight years professional ARF experience. While we acknowledge these relationships appear small, they resulted in reductions in rMSSD upwards of ~13 ms and were consistent across all levels of analysis conducted in the current investigation. Thus, while we deem these findings to be practically important in the context of assessing the relation between training and competition load and HRV within team-sport, they should be interpreted within a holistic training load monitoring program, and not in isolation. Nonetheless, our findings are in agreement with Ye et. al. (2022) who showed that an increased sprint volume was associated with a reduction in HRV (Ye et al., 2022). Given that near-maximal sprinting requires a high metabolic demand (Gibala & Hawley, 2017) which can induce high physiological stress (Peart et al., 2013) and neuromuscular fatigue (Baumert et al., 2021) it stands to reason that an increase in sprint distance would result in a reduction in HRV. Furthermore, during the early phases of the pre-season preparation period, when athletes are still building resilience to training load (and sprinting), athletes may be more susceptible to the negative side-effects (i.e., heightened fatigue) of increasing sprint workload and this was reflected in a significant reduction in the change in waking HRV. These data demonstrate that practitioners should monitor HRV during periods of increased or novel sprint work to allow for the manipulation of future training and recovery sessions in an attempt to optimise the training stimulus.

To this point, our results highlight an increase in sprint distance is associated with a greater reduction in waking HRV during the early pre-season phase (compared to all other season periods). This result could be reflective of a generalised training plan, whereby a greater emphasis is placed on total volume metrics in the early phases of pre-season (Fisher et al., 2022) as opposed to sprint distance and thus changes in sprint load may elicit greater physiological stress compared to other periods across the season. When conducting analysis accounting for years of professional experience within the professional ARF system, it is unclear why relationships between sprinting and change in waking HRV were only witnessed in athletes who had eight or more years of professional playing experience. However, while direct links between our data and the likelihood of injury cannot be made, previous investigations have shown increasing age is associated with greater risk of injury (Prior et al., 2009) where older athletes are 2.8 to 4.4 times more likely to suffer a hamstring injury (Gabbe, Bennell, & Finch, 2006; Gabbe, Bennell, Finch, Wajswelner, et al., 2006) but also that reductions in HRV may be indicative of increased likelihood of musculoskeletal injury (Gisselman et al., 2016). Together, there is the potential that older athletes are less adept at recovering from central and/or peripheral fatigue induced by increased sprinting load. This maladaptive response could contribute to increased hamstring injury risk owing to changes in capacity of voluntary activation of muscle, excitation-contraction coupling and contractile (force production) mechanisms (Bengtsson et al., 2018; Boyas & Guével, 2011; Marqués-Jiménez et al., 2017). However, this notion requires further investigation as associations from the current investigation and injury risk cannot be drawn. Nonetheless, we provide robust evidence that increased sprinting load leads to an imbalance between sympathetic and parasympathetic autonomic nervous system activity, particularly within players with greater than eight years of experience within the professional ARF system. Appropriate planning and adjusting the emplaced sprint load (guided by HRV monitoring and other factors), accounting for an appropriate stimulus to minimise the likelihood of soft-tissue injury (F. O'Connor et al., 2019) presents as an important aspect of holistic training load programs. Further, during periods of heightened stress where training load is increased (and HRV is lowered), practitioners can use the present results to guide the implementation of interventions that will accelerate recovery processes. This can be done by first and foremost promoting good sleep hygiene practices (Pitchford et al., 2017) (increasing sleep duration may increase HRV) (Mishica et al., 2021) and appropriate nutritional interventions to enhance recovery (Beck et al., 2015) among other mechanisms which may decrease overall stress and increase HRV.

When accounting for years of experience within the professional ARF system, greater total distance on the previous day and across the previous seven days resulted in a decrease in HRV in first-year players, and across the previous three- and seven-days in the fifth-to-seventh year players. It is plausible that greater load would result in a greater accumulation of fatigue within team-sport athletes, and given the known relationship between duration and total distance completed during team-sport training (Bartlett et al., 2017) the reductions in HRV witnessed within our analysis are unsurprising. Moreover, owing to the increased demands of professional sporting environments, compared to elite youth pathways (Reynolds et al., 2021) First-Year players may be more susceptible to fluctuations in load and the accumulation of load while resilience to the emplaced load is acquired. In addition, these known relationships may in part explain the increases in HRV we have witnessed following the completion of greater HSR distances within periods across the previous seven days, within specific training age groups. One possible explanation for this is that during training sessions there may have been a more intentional redistribution of running towards that of HSR and less on overall total distance. When considering the known positive relationships between accumulation of fitness and HRV (Costa et al., 2022) it could be that players within this particular cohort were accruing HRV-determined fitness adaptation during periods where there was a greater proportion of HSR completed (relative to Total Distance) within training sessions. However, it was beyond the scope of the current investigation to assess these relations.

In the current investigation, HRV was quantified via photoplethysmographic recording via a smartphone camera placed on top of the index fingertip. While it is acknowledged that this method of data capturing is not considered the gold standard in terms of heart rate variability monitoring typically utilised within clinical settings (Voss et al., 1995) it presents as a simple to administer and practical method of monitoring that can be employed on a daily basis in team sport environments. To the best of our knowledge, no other monitoring techniques that provide information regarding the balance of sympathetic and parasympathetic activity can be as efficiently and effectively employed within large athlete cohorts. Further, the method of HRV quantification utilised has been proven to be valid and reliable in comparison to chest strap monitoring and 12-lead ECG during laboratory trials and has been shown to be effective at evaluating changes in subjective training load in large-scale (five-year data acquisition, ~9 million measurements from 28,175 users) general population settings (Altini & Plews, 2021). Thus, our results suggest that smartphone PPG-derived HRV may be adequate for discriminating between fluctuations in training and competition load, and may be a feasible option that provides valuable information on the stress response in a professional team-sport environment if contextualised within an overall load monitoring program. Indeed, the information garnered from the appropriate administration of a PPG-derived HRV monitoring program has the potential to provide practitioners with nuanced viewpoints regarding the stress-recovery response of individual athletes that alleviates many of the inherent limitations of self-report psychometric questionnaires (Coventry et al., 2023; Gallo et al., 2017) and more cumbersome and time-consuming neuromuscular fatigue monitoring techniques.

While our data highlight significant relations between load completed across a 7-day period, we acknowledge that the results may have been influenced by HRV being a measure of "overall stress" (encompassing psychological and physical stress) as opposed to physical training stress alone (Kim et al., 2018). For example, professional athletes are exposed to wide-ranging and divergent forms of psychological stress (Gulliver et al., 2015; Hammond et al., 2013) that can all lead to negative psychological wellbeing in acute and chronic forms. To the best of our knowledge, this is the first investigation to measure associations between load and HRV in an elite team-sport over a period encompassing two complete pre-seasons and in-season periods. Thus, while it was not possible to quantify psychological stress in the current investigation, athletes would have likely been exposed to varying degrees of psychological stress at points throughout the data collection period, that are not reflected in training load data. Moreover, our data only highlights the relation between on-pitch training load and waking-HRV responses, and thus does not encompass load accrued during other physiologically stressful activities commonly encountered by professional athletes, e.g., gym-based strength and conditioning sessions. Finally, we acknowledge that the findings are limited to this particular athlete cohort and may not be wholly representative of athlete responses within other professional sports, or within different professional ARF settings. Together, future investigations should endeavour to quantify relationships between gym-based training load (i.e., total tonnage lifted), on-pitch training load and where possible psychological stress and waking HRV to provide a holistic overview of the athlete's response to the demands of professional team-sport. Nonetheless, the information provided within this manuscript can be utilised by practitioners and coaches alike to appropriately plan, prescribe and monitor team-sport training load. Indeed, while we acknowledge that the results witnessed may be reflective of the athlete cohort monitored, we provide evidence to suggest that the utilisation of PPG derived HRV monitoring is sensitive to fluctuations in training load in professional team-sport athletes.

Conclusion

The data presented within this manuscript show the complexity of load monitoring in team-sport environments. While we present significant relations between standard measures of load and changes in HRV, these relations are complex and require contextualisation. Nonetheless, we show the potential applicability of heart rate variability monitoring using a smartphone application that relies on photoplethysmography data capturing techniques in a professional team-sport environment. The results presented within this manuscript may help guide practitioners in professional team-sport settings to select appropriate monitoring techniques that will help inform training practices.

Informed consent and data availability

Informed consent and consent to publish were obtained from all participants prior to data collection commencing. Ethical approval was granted by Bond University Human Research Ethics Committee (FO00007) and all procedures adhered to the declaration of Helsinki. The data that support the findings of this study are openly available in Figshare at 10.6084/m9.figshare.23936430.

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