

MONITORING HEART RATE VARIABILITY IN ELITE COLLEGE FOOTBALL PLAYERS
THROUGHOUT THE PREPARATORY AND COMPETITIVE SEASON

by

ANDREW A. FLATT

MICHAEL R. ESCO: COMMITTEE CHAIR

RYAN L. EARLEY

MICHAEL V. FEDEWA

JONATHAN E. WINGO

JAMES B. ROBINSON

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ABSTRACT

Vagally-mediated heart rate variability (lnRMSSD) reflects cardiac-parasympathetic modulation and may be a useful marker for reflecting recovery status and training adaptation in football players. Three studies were conducted to evaluate lnRMSSD responses to training based on playing position (SKILL, MID-SKILL and LINEMEN) among an elite college football team during three distinct phases of training including the off-season (Spring camp), preseason camp and the in-season competitive period. The first study evaluated daily and chronic lnRMSSD responses to training during Spring camp. Following ~20 h of recovery from a football practice, a significant reduction in lnRMSSD for LINEMEN was observed, while lnRMSSD for SKILL and MID-SKILL returned to near or within baseline values. Individual changes in lnRMSSD from baseline to 20 h post-training were significantly related to body mass with greater lnRMSSD reductions occurring among heavier players and vice versa. Chronic responses showed that individual coefficient of variation of lnRMSSD derived from the entire 4-week Spring camp was significantly inversely related to individual mean training load after adjusting for body mass. The second study evaluated daily lnRMSSD and perceived wellness responses to a 13-day intensive preseason training camp in hot and humid conditions. After the first few days of training, decrements in lnWellness and increases in lnRMSSD, peaking on Day 12 following a day of passive rest among SKILL and LINEMEN were observed. The peak in lnRMSSD was associated with the return of lnWellness to Day 1 values. MID-SKILL showed no meaningful changes in lnRMSSD while their lnWellness remained chronically suppressed throughout the duration of

preseason camp. The third study evaluated the daily lnRMSSD response to the most intense training session of the week across three separate weeks during the first month of the competitive season. Compared to resting values, lnRMSSD ~20 h following training was significantly reduced for LINEMEN and MID-SKILL but not for SKILL. The individual change in lnRMSSD from rest to 20 h post training was significantly related to both body mass and training load. In conclusion, the lnRMSSD response to training among elite football players depends on playing position, body mass, training load and training phase. Subjects with greater body mass and lower mean training loads tend to show the largest reductions in lnRMSSD while subjects with lower body mass and higher mean training loads tend to show smaller daily changes in lnRMSSD. While these lnRMSSD responses to training were consistent during Spring camp and during the early in-season competitive phase, this trend was obscured during preseason training in hot and humid conditions. Rather than decreasing with accumulated fatigue, lnRMSSD tended to increase. Thus, heat acclimatization responses during preseason camp may prevent typical training-induced reductions in lnRMSSD observed during Spring camp and in-season.

DEDICATION

This dissertation is dedicated to my beautiful and incredible wife, Jen Flatt, who has been by my side every step of the way along this journey. This is also dedicated to my parents (Russell and Carol Flatt) and my parents-in-law (Chris and Cheryl Fleming) who have provided me with the love and support that made my pursuit of graduate studies possible. Finally, this is dedicated to all football coaches and support staff who prioritize the health and well-being of their athletes.

LIST OF ABBREVIATIONS & SYMBOLS

HRV	heart rate variability
lnRMSSD	natural logarithm of the root mean square of successive R-R interval differences
Δ lnRMSSD	change in lnRMSSD
CV	coefficient of variation
PL	PlayerLoad™
BL	baseline
SKILL	positional group comprised of receivers and defensive backs
MID-SKILL	positional group comprised of linebackers, running backs and tight-ends
LINEMEN	positional group comprised of offensive and defensive linemen
$\dot{V}O_{2max}$	maximal oxygen uptake
Wellness	averaged value from subjective sleep quality, soreness, fatigue, stress and mood
au	arbitrary units
ES	effect size
CL	confidence limits
kg	kilograms
ms	milliseconds
h	hour
min	minute

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CHAPTER 1

INTRODUCTION

American college football players are regularly exposed to rigorous training schedules in an effort to enhance physical performance capacities. The physical demands of football require players to perform repeated efforts of maximal intensity with physical contact and collisions occurring regularly during play.^{1,2} The physiological impact of football training is further exacerbated by heat stress due to environmental conditions, protective equipment requirements and the large body mass of players.³ Thus, football players are at risk of excess fluid loss during training which is associated with an increased risk of cardiac strain.⁴ Furthermore, competitive game demands require players to cover distances between 3 – 6 km depending on positional group, which may be exceeded during daily training sessions.⁵ With football training often occurring on consecutive days, players are given less than 24 hours between sessions. Whether this time-period is sufficient for adequate recovery has not been well studied.

Football players vary in both physical and performance characteristics due to unique positional requirements. For example, receivers and defensive backs (SKILL) have the greatest running distance requirements and thus tend to have the lowest body mass and the greatest aerobic fitness level among positional groups.^{1,5,6} In contrast, linemen (LINEMEN) have the lowest running requirements but regularly encounter physical bouts in which they must displace their opponent in an effort to gain or defend field position.^{5,7} LINEMEN therefore have the greatest body mass and lowest aerobic fitness level of the various positional groups.⁶ Linebackers, running

backs and tight-ends (MID-SKILL) experience demands characteristic of both SKILL and LINEMEN and thus tend to display physical characteristics intermediate to these positions.^{1,5,6} Body mass, physical demands and physiological responses to training vary by position with LINEMEN experiencing the greatest fluid loss and thermoregulatory challenge during training.^{3,8} Therefore, it is possible that daily recovery patterns may also differ among positions, however this hypothesis has yet to be investigated.

Time constraints in the applied football setting limit the use of training status variables that are invasive or time-consuming (e.g., blood or salivary biomarkers), highlighting the need for practical and convenient monitoring tools for daily implementation. Quantification and monitoring of external training load via microtechnology (i.e., global positioning systems and tri-axial accelerometers) provides minimal burden to athletes and is becoming more popular among football teams.^{2,5,9} Knowledge of training load imposed on football players provides staff with information regarding training dose and may aid in evaluating injury risk⁹ and fitness capacity.¹⁰⁻¹² However without information regarding individual physiological responses, its practical use may be limited. For example, excess load, insufficient load and unvarying load have each been linked to increased injury risk among athletes.^{9,10,13} Further, inferring training status from microsensor-derived movement parameters would be difficult in football due to its chaotic nature. Thus, investigation into practical, non-invasive physiological markers reflective of recovery status that can be used in conjunction with training load for daily monitoring is needed.

Heart rate variability (HRV) is an objective, physiological marker that reflects cardiac-autonomic regulation and can be obtained conveniently in the field with mobile applications.^{14,15} Cardiac-parasympathetic modulation inferred from vagal-related HRV is suppressed during exercise and in the acute stages of recovery.^{16,17} Restoration of HRV to pre-exercise levels may

reflect recovery of cardiovascular-autonomic homeostasis and is sometimes used to guide training.^{18,19} Cardiac-parasympathetic recovery from exercise can take between 24-48 hours and is affected by factors such as individual fitness level, exercise intensity and fluid balance.¹⁶ Each of these factors (i.e., fitness, movement demands of training and fluid loss) vary according to football playing position. This may suggest that HRV responses to training would also differ based on position. However, HRV responses to training in football players have not previously been investigated.

Training load and frequency of football training vary throughout the annual cycle based on league regulations and proximity to competition. As such, three primary phases exist for college football teams in which football practices regularly occur. This includes Spring camp, preseason camp and the in-season competitive period. Spring camp lasts four consecutive weeks with football practices being held 3 – 4 times per week. Preseason camp occurs in early August, lasts approximately two weeks and involves 1 – 2 practice sessions per day in hot and humid conditions. The in-season competitive phase spans from September to December with 4 – 5 training sessions and one competition occurring weekly. It is currently unknown if HRV responses to training differ based on training phase in football players. This research is needed because increases in vagally-mediated HRV among athletes are often interpreted as an improvement in recovery and training status.¹⁸ However, factors such as heat acclimatization responses may attenuate fatigue-related fluctuations in HRV leading to misinterpretation of the data.^{20,21}

While HRV has shown promise as a monitoring tool for reflecting training responses throughout different phases of training among various sports,²²⁻²⁶ its usefulness for reflecting recovery and adaptive responses among American football players is unknown. Therefore, the purpose of this dissertation was to evaluate daily and chronic HRV responses to training

throughout various training seasons among an elite college football team. Specific aims were as follows:

Study 1: 1) To evaluate the effects of football training on HRV following ~20 h of recovery among positional groups and 2) to assess relationships between chronic external training load and chronic HRV trends throughout an annual Spring training camp of an elite college football team.

Study 2: To monitor daily HRV and psychometric responses to training among positional groups of an elite college football team during a 13-day preseason camp in hot and humid conditions.

Study 3: 1) To assess the daily HRV response to intense in-season training among elite college football players and 2) to evaluate if body mass and training load relate with HRV responses.

CHAPTER 2

DAILY AND CHRONIC HEART RATE VARIABILITY RESPONSE TO TRAINING IN ELITE FOOTBALL PLAYERS DURING SPRING CAMP

ABSTRACT

Heart rate variability (HRV) responses to daily and chronic training have not been explored in American football players. **PURPOSE:** To evaluate daily HRV responses to football training among positional groups comprised of backs and receivers (SKILL; n = 11), running backs, linebackers and tight-ends (MID-SKILL; n = 9) and linemen (LINEMEN n = 5) from an elite college football team. An additionally aim was to quantify relationships between chronic (i.e., 4-week) HRV trends and training load values. **METHODS:** Baseline vagal-HRV (lnRMSSD_BL) was compared with lnRMSSD acquired 20 h following a football practice (lnRMSSDpost20) among positional groups with a linear mixed model. Pearson and partial correlations were used to quantify relationships between chronic mean and coefficient of variation (CV) of lnRMSSD (lnRMSSD_chronic and lnRMSSDcv, respectively) with the mean and CV of PlayerLoad™ (PL_chronic and PL_cv, respectively). **RESULTS:** A significant position × time interaction was observed for lnRMSSD. lnRMSSD_BL was significantly higher than lnRMSSDpost20 for LINEMEN while differences for SKILL and MID-SKILL were not statistically significant. After adjusting for body mass, a significant negative relationship between lnRMSSDcv and PL_chronic was observed. **CONCLUSION:** ~Twenty hours following a football practice, lnRMSSD values were suppressed for LINEMEN, possibly indicating inadequate recovery. Players with a lower

chronic training load throughout Spring camp experienced greater daily fluctuation in lnRMSSD (i.e., lnRMSSDcv) and vice-versa. Thus, training capacity appears to be a determinant of lnRMSSD trends in football players.

INTRODUCTION

Accessibility to novel sports science technology has facilitated a growing interest in the monitoring of athletic training status across numerous sports disciplines. Variables such as training load and markers of recovery provide context and rationale for modifying training programs to manage fatigue, reduce the risk of injury and optimize performance adaptation in athletes.¹ Despite a demanding training schedule and high injury rate in American football,² research pertaining to training status monitoring among football players pales in comparison with sports such as soccer and rugby.³

Unique features of football include its anaerobic, intermittent style of play⁴ and variation in body mass among positions that ranges between 88 – 136 kg.⁵ Football is a collision sport, involving intermittent bouts of high intensity activity including sprinting, jumping, tackling and rapid changes of direction. Football players are typically categorized based on position with receivers and defensive backs (SKILL), running backs, linebackers and tight-ends (MID-SKILL) and linemen (LINEMEN) typically comprising each group.⁴ These positional groups have unique physical and performance characteristics^{6,7} as a result of varying movement demands during practice and competition.⁸⁻¹⁰ The substantial physiological strain experienced by athletes from football practice and competition⁴ warrants further research into effective and practical player monitoring strategies within this population.

Wearable devices utilizing global position systems and integrated tri-axial accelerometers (microtechnology) are capable of measuring full-body displacement, velocity, acceleration and direction of movement during sports play.³ Wearable microtechnology is attractive to coaching staff because the physical demands and load of a competition or training session can be quantified with minimal burden to the athlete. Though training load monitoring is becoming more popular in football,⁸⁻¹⁰ its use in conjunction with recovery status indicators among football players has not been investigated. This research is needed because external training load does not provide information regarding internal physiological responses and there exists substantial inter-individual variation in responses and adaptation to training.¹¹ Thus, a comprehensive approach that includes objective physiological markers in addition to training load may offer a more complete assessment of training status, providing insight regarding training dose and physiological response.

A recovery status metric gaining popularity among sports teams is resting heart rate variability (HRV), a non-invasive measure of cardiovascular-autonomic control. Vagally-mediated HRV is considered a global marker of homeostasis and reflects cardiovascular recovery following a training session.¹² For example, vagal-HRV suppression is observed for 24-48 hours following intense training¹² with the return to baseline possibly reflecting the optimal state for subsequent intensive training to optimize cardiovascular adaptations.^{13,14} Acute (minutes to hours) vagal-HRV recovery is mediated by clearance of lactate and metabolites^{15,16} while intermediate recovery (24-48 hours) to \geq baseline has been related to baroreflex-mediated increases in parasympathetic activity due to exercise-induced plasma volume expansion.^{17,18} Fitness level appears to be an important determinant of cardiac-parasympathetic recovery following exercise as less aerobically fit individuals experience delayed post-exercise return of vagal-HRV to baseline relative to individuals with greater aerobic fitness.^{12,19,20} Since fitness level,²¹ body mass,⁵ as well

as fluid balance and thermoregulatory responses to training vary among positional groups in football,²² it is possible that daily cardiac-autonomic responses inferred from vagal-HRV likely also differ. However, this hypothesis has yet to be investigated.

Greater daily fluctuation in cardiac-parasympathetic activity (assessed by the coefficient of variation, CV) is related to lower maximal oxygen uptake ($\dot{V}O_{2max}$) and intermittent running performance in soccer players.²³⁻²⁵ In team-sports, an athlete's chronic external training load (i.e., 4-week average) is sometimes used as an indicator of fitness level.²⁶ Among football players, SKILL accumulate the greatest running loads followed by MID-SKILL and then LINEMEN.⁸ Not surprisingly, $\dot{V}O_{2max}$ values follow the same pattern with highest values observed in SKILL followed by MID-SKILL and LINEMEN.²¹ Hypothetically, football players who perform greater external training loads should have a greater chronic (i.e., 4-week) mean and lower CV of vagal-HRV. This would build on previous findings that less fit individuals experience greater perturbations in cardiac-autonomic homeostasis than more fit individuals.^{23,24} However, no previous studies have evaluated relationships between chronic external training load and chronic vagal-HRV trends in football players.

Research into both daily and chronic HRV responses to football training is needed to determine if HRV has any practical use for football teams. Therefore, the purpose of this study was to evaluate the effects of football training on daily vagal-HRV among elite college football players. A secondary aim was to assess relationships between football players' chronic external training load and chronic vagal-HRV trends (i.e., mean and CV) from an annual Spring training camp.

METHODS

Subjects

Twenty-Five Division 1-A football players from a National Collegiate Athletics Association's Southeastern Conference team volunteered for this study. Only team members ≥ 18 years of age and on athletic scholarship were included in this study. Subjects were grouped based on position as previously described⁴ (SKILL: $n = 11$; age = 20.3 ± 1.3 years; height = 187.7 ± 4.0 cm; weight = 90.2 ± 4.3 kg; MID-SKILL: $n = 9$; age = 20.4 ± 1.3 years; height = 188.8 ± 5.5 cm; weight = 103.8 ± 4.4 kg; LINEMEN: $n = 5$; age = 21.6 ± 0.9 years; height = 192.5 ± 2.8 cm; weight = 131.1 ± 10.6 kg). All subjects obtained medical clearance from the sports medicine staff for participation in football training. Informed consent was obtained from each subject for their participation in this study. Ethical approval for was granted by the institutional review board for human participants.

Study Design

This was an observational study that took place during an annual Spring training camp of an elite college football team. The research design and methodology was devised according to the pre-determined program and structure of the training camp, which the researchers did not influence. Vagal-HRV and external training load were acquired each football training day throughout the 4-week Spring training camp. For the first objective, we assessed the effect of a football training session on vagal-HRV following ~ 20 hours of recovery relative to the typically provided ≥ 48 h recovery duration. For the second objective, relationships between chronic external training load and chronic vagal-HRV (i.e., mean and CV) from the 4-week camp were evaluated.

Spring Camp

Spring camp involved four consecutive weeks of football training. Two-hour football practices were held on Monday, Wednesday and Friday of week 1; Monday, Wednesday, Friday and Saturday of weeks 2 and 3; and Tuesday and Thursday of week 4. A full-length scrimmage was held on Saturday of week 4. Forty-five-min full-body resistance training sessions of moderate intensity were held on Tuesdays and Thursdays throughout weeks 1-3. Sundays were reserved for passive rest throughout the training camp. Prior to Spring camp, all team members participated in an 8-week off-season strength and conditioning program. Average outdoor temperatures during practice were recorded.

External Training Load

Training load parameters were obtained from football sessions via tri-axial accelerometers (minimaxX, Catapult Innovations, Melbourne, Australia) at a sampling rate of 100 Hz. These devices measure full-body acceleration in three planes: posterior/anterior, medial lateral and vertical.²⁷ Subjects wore the same device for each practice session, positioned between the scapulae, fixed in place on their shoulder pad in a custom-built cartridge. Following each practice session, training load data were downloaded to a laptop for analysis using accompanying software (Catapult Innovations). The training load parameter used for this study was total PlayerLoadTM. This parameter reflects total external workload including running, jumping, changes of direction and body contacts; has been related to injury occurrence in football players;¹⁰ and has been shown to be a reliable metric within and between devices (CV values <2%) for quantifying physical activity in team-sports.²⁸ PlayerLoadTM is expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors and divided by 100.²⁸

Heart Rate Variability

HRV data were acquired each day that football practice was held. Measures were obtained in the athletic training facility at least 90 min after team breakfast and before any physical activity took place. Subjects verbally confirmed that caffeinated beverages were not consumed prior to data acquisition. HRV recordings were obtained while subjects were seated comfortably on an athletic training table prior to receiving treatment (e.g., ankle taping). Once seated, subjects were handed a tablet (iPad2, Apple Inc. Cupertino, California, USA) with an optical pulse-wave finger sensor (HRV Fit LTD. Southampton, UK) inserted into the headphone slot in preparation for the HRV recording. The finger sensor detects pulse-rate via photo-plethysmography and has demonstrated acceptable agreement with electrocardiograph-derived HRV in previous comparisons.^{29,30} Subjects were verbally instructed to insert their left index finger into the cuff of the finger sensor, then to select their name from the team roster previously uploaded onto the iPad application (ithlete™ Team, HRV Fit LTD. Southampton, UK) by a researcher. The subjects then initiated a supervised HRV measure while remaining quiet and breathing naturally. HRV data were automatically uploaded from the tablet to the web-based interface of the team application for analysis. The application provides a time domain vagal-HRV index, the logarithm of the root mean square of successive RR intervals (lnRMSSD) which is multiplied by 20 to fit an approximate 100-point scale for simplified interpretation.³¹ The lnRMSSD is the preferred HRV parameter for monitoring athletes in field settings for reasons described previously.³² The application is equipped with an irregular pulse-rate detection algorithm which excludes inter-pulse intervals <500 ms and >1800 ms.³¹ Subjects were seated for at least 1-min prior to a 1-min HRV recording.^{33,34} Ultra-short (i.e., 1-min) lnRMSSD recordings suitably reflect traditional 5-min lnRMSSD measures in collegiate³⁵ and professional athletes when obtained at the training facility.^{34,36} In addition, seated,

ultra-short lnRMSSD obtained at the training facility following a 2-h fast has been shown to provide acceptable intra- and inter-day reliability in professional collision-sport athletes³⁷ while also demonstrating sensitivity to training-induced changes.³⁶

Statistical Analysis

Data normality was assessed with the Shapiro-Wilk test. Residuals for all variables met the assumption of normality ($p > 0.05$). To evaluate the effect of a football training session on lnRMSSD, baseline lnRMSSD (lnRMSSD_BL) was compared to lnRMSSD acquired the day following a football training session (i.e., 20 h rest, lnRMSSDpost20). The intra-individual mean lnRMSSD for each positional group from Monday, Wednesday and Friday of Week 2 represented lnRMSSD_BL as each of these football training sessions were separated by ≥ 48 h. Saturday of the same week represented lnRMSSDpost20 as it was preceded by only ~ 20 h rest. A general linear mixed model was used to examine variation in lnRMSSD among positions (i.e., SKILL, MID-SKILL and LINEMEN) and between lnRMSSD_BL and lnRMSSDpost20. Position was included as a fixed main effect, time (lnRMSSD_BL vs. lnRMSSDpost20) was included as a fixed within-subjects repeated measure, the position \times time interaction was included as a fixed main effect, and athlete identification was included as a random effect. Tukey HSD was used for post-hoc analyses. In addition, the magnitude of the change in lnRMSSD between conditions was evaluated using Cohen's d effect sizes (ES) \pm 90% confidence limits (CL).³⁸ ES were interpreted qualitatively as follows: < 0.2 , trivial; 0.2 – 0.59 , small; 0.6 – 1.19 , moderate; 1.2 – 1.9 , large; > 2.0 , very large.³⁹ The effect was deemed unclear if the CL crossed the threshold for both substantially positive (0.20) and negative (-0.20) values.⁴⁰ Individual change variables for lnRMSSD were calculated (lnRMSSDpost20 – lnRMSSD_BL, Δ lnRMSSD). The relationship between Δ lnRMSSD and body

mass was quantified via Pearson correlation. PlayerLoadTM values derived from the same days as lnRMSSD_{BL} were compared among positions with a one-way ANOVA and Tukey HSD post-hoc analysis.

For the second objective concerning longitudinal analysis, Pearson correlations were used to quantify relationships between daily mean and CV of PlayerLoadTM, (PL_{chronic} and PL_{cv}, respectively) with the daily mean and CV of lnRMSSD (lnRMSSD_{chronic} and lnRMSSD_{cv}, respectively) derived from the entire 4-week training camp. A compliance rate of $\geq 70\%$ for lnRMSSD recordings was required to determine chronic values.^{41,42} Actual compliance was $92 \pm 7.3\%$. The thresholds used for qualitative assessment of the correlations were: <0.1 , trivial; $0.1-0.29$, small; $0.3-0.49$, moderate; $0.5-0.7$, large; $0.7-0.89$, very large; >0.9 nearly perfect.³⁹ Statistical procedures were carried out using JMP Pro 13 (SAS Institute Inc. Cary, North Carolina, USA) and Excel 2016 (Microsoft Corp. Redmond, Washington, USA). Data are reported as mean \pm SD unless noted otherwise.

RESULTS

A significant effect was found for PlayerLoadTM values derived from the same days as lnRMSSD_{BL} ($F_{2,22} = 18.20$, $p < 0.0001$). Baseline PlayerLoadTM values for SKILL, MID-SKILL and LINEMEN were 623.7 ± 60.6 , 556.8 ± 53.6 and 450.0 ± 29.2 , respectively. Tukey HSD post-hoc comparisons revealed that PlayerLoadTM values for SKILL were significantly higher than LINEMAN ($p < 0.0001$, $ES = 3.27 \pm 1.27$, *Very Large*) and MID-SKILL ($p = 0.029$, $ES = 1.16 \pm 0.79$, *Moderate*). Additionally, MID-SKILL baseline PlayerLoadTM was significantly greater than LINEMEN ($p = 0.005$, $ES = 2.25 \pm 1.10$, *Large*).

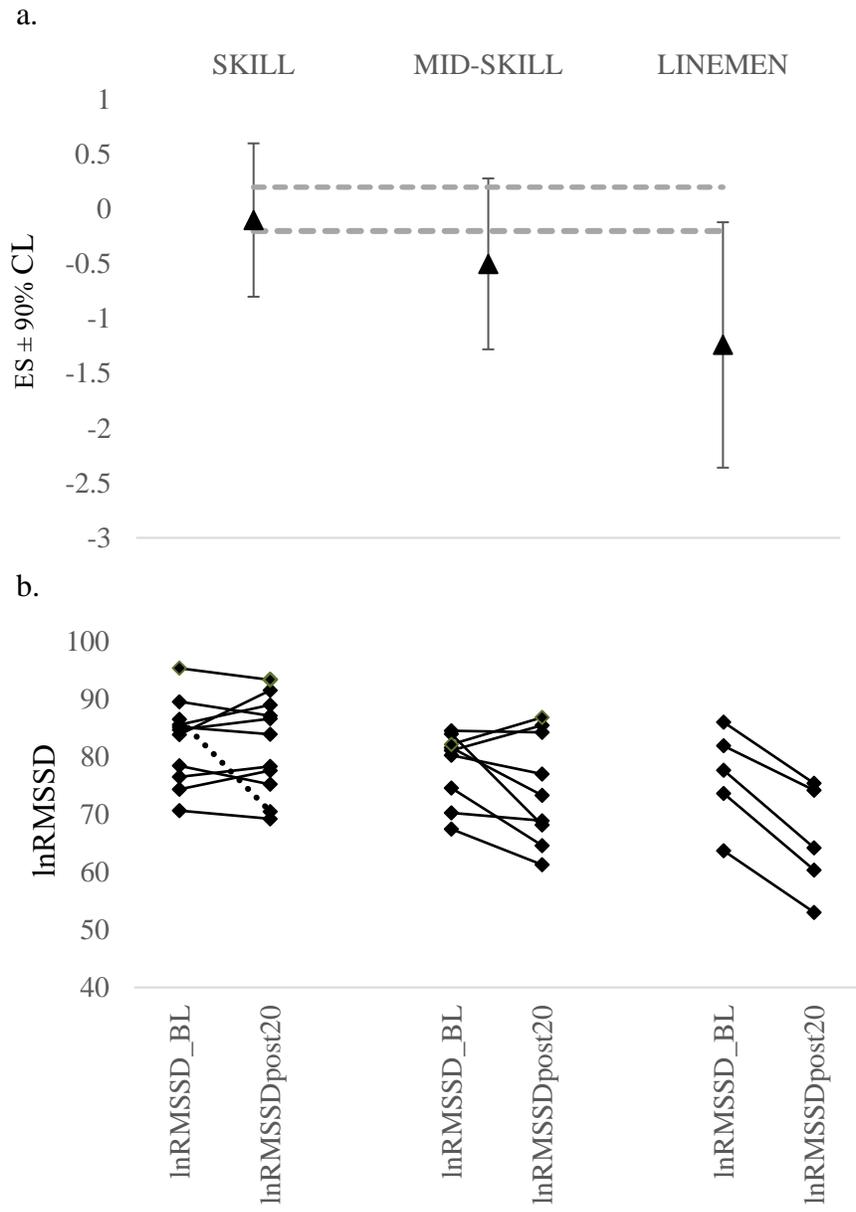
A significant position \times time interaction was found for lnRMSSD. Model effects and lnRMSSD values are presented in Table 2.1. Tukey HSD post-hoc comparisons revealed that lnRMSSD_BL was significantly higher than lnRMSSDpost20 for LINEMEN ($p < 0.01$; ES = -1.24 ± 1.12 , *Large*) while differences for SKILL ($p = 0.998$; ES = -0.10 ± 0.70 , *Unclear*) and MID-SKILL ($p = 0.343$; ES = -0.50 ± 0.78 , *Unclear*) were not statistically significant. ES and individual lnRMSSD responses are graphically displayed in Figure 2.1a. and 2.1b., respectively.

Table 2.1. Model effects and mean and standard deviation for the natural logarithm of the root mean square of successive R-R interval differences (lnRMSSD) among and between positional groups and days.

Model effect	F	df	P	Mean \pm SD lnRMSSD		
Position	4.24	2, 22	0.028	SKILL: 82.4 \pm 7.6	MID-SKILL: 76.4 \pm 8.0	LINEMAN: 71.0 \pm 10.3*
Time	18.47	1,22	<0.001	BL: 80.0 \pm 7.3	POST: 76.0 \pm 10.7 [€]	
Position \times Time	5.46	2, 22	0.012	SKILL BL: 82.8 \pm 7.2 SKILL Post: 82.0 \pm 8.3	MID-SKILL BL: 78.4 \pm 6.2 MID-SKILL Post: 74.4 \pm 9.5	LINEMAN BL: 76.6 \pm 8.6 LINEMAN Post: 65.4 \pm 9.5 [¥]

df = degrees of freedom; lnRMSSD = natural logarithm of the root mean square of successive R-R interval differences; BL = baseline; Post = 20 h post training. * = significantly lower than SKILL ($p < 0.05$); [€] = significantly lower than BL ($p < 0.05$); [¥] = significantly lower than BL for LINEMEN.

Figure 2.1.



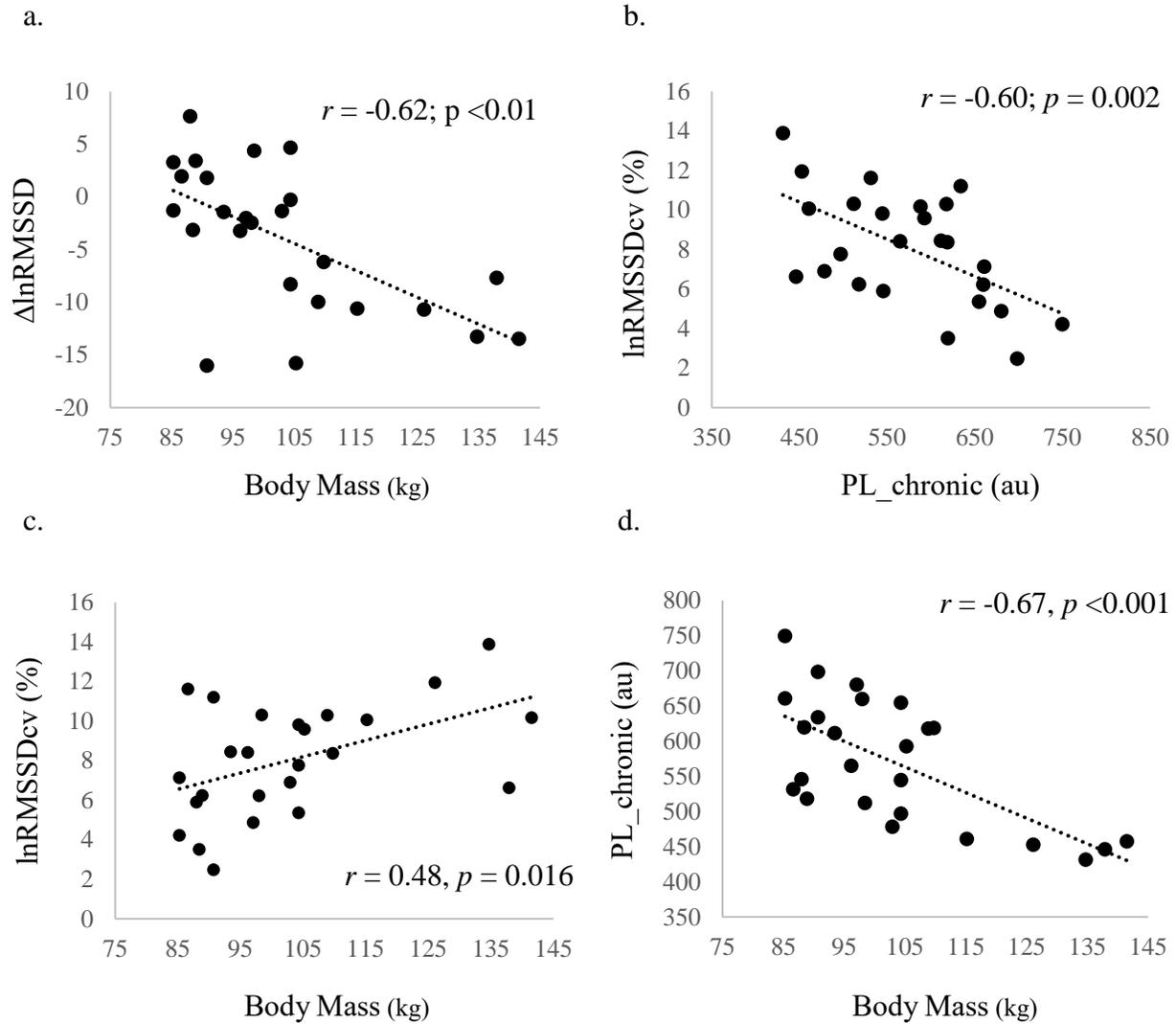
a) Effect size ± 90% confidence limits (ES ± 90% CL) comparisons of baseline natural logarithm of the root mean square of successive R-R interval differences (lnRMSSD_BL) with lnRMSSD following 20 hours of rest (lnRMSSDpost20) among positional groups. The horizontal dashed lines represent thresholds for a *Small* effect (0.20 - -0.20).

b) Individual lnRMSSD_BL and lnRMSSDpost20 values among positional groups. The dashed line represents a SKILL player (Athlete B) who had surgery in the preceding months and therefore was unable to fully participate in off-season training.

A significant main effect for position was found for lnRMSSD (Table 2.1.). lnRMSSD for SKILL was significantly greater than LINEMEN ($p < 0.05$; $ES = 1.35 \pm 0.96$; *Large*). A significant main effect for time was also observed for lnRMSSD (Table 2.1.). Evaluated as a group ($n = 25$), lnRMSSD_BL was significantly higher than lnRMSSDpost20 ($p < 0.05$; $ES = 0.44 \pm 0.47$; *Small*). A significant negative relationship between $\Delta \ln RMSSD$ and body mass was observed ($n = 25$; $r = -0.62$; $p < 0.01$, *Large*) (Figure 2.2a.) indicating that larger reductions in lnRMSSD occurred among players with greater body mass.

lnRMSSD_chronic did not show a significant relationship with PL_chronic ($n = 25$; $r = 0.33$, $p = 0.109$), PLcv ($n = 25$; $r = 0.16$, $p = 0.436$), or body mass ($n = 25$; $r = -0.36$, $p = 0.073$). There was a significant negative relationship between lnRMSSDcv and PL_chronic ($n = 25$; $r = -0.60$, $p = 0.002$, *Large*) (Figure 2.2b.) and a significant positive relationship between lnRMSSDcv and body mass ($r = 0.48$, $p = 0.016$, *Moderate*) (Figure 2.2c.). lnRMSSDcv did not significantly relate with PLcv ($r = 0.025$, $p = 0.907$). Body mass showed a significant negative relationship with PL_chronic ($r = -0.67$, $p < 0.001$, *Large*) (Figure 2.2d.). After adjusting for body mass via partial correlation analysis, the negative relationship between lnRMSSDcv and PL_chronic remained significant ($r = -0.42$, $p = 0.034$, *Moderate*).

Figure 2.2.



a) Scatterplot representing the relationship between the difference in natural logarithm of the root mean square of successive R-R interval differences from baseline ($\ln \text{RMSSD}_{\text{BL}}$) and 20 hours post-training ($\ln \text{RMSSD}_{\text{post20}}$) (i.e., $\ln \text{RMSSD}_{\text{post20}} - \ln \text{RMSSD}_{\text{BL}} = \Delta \ln \text{RMSSD}$) and body mass.

b) Scatterplot representing the relationship between the coefficient of variation of $\ln \text{RMSSD}$ ($\ln \text{RMSSDcv}$) and average PlayerLoad™ ($\text{PL}_{\text{chronic}}$) from the entire 4-week camp.

c) Scatterplot representing the relationship between $\ln \text{RMSSDcv}$ and body mass.

d) Scatterplot representing the relationship between $\text{PL}_{\text{chronic}}$ and body mass.

DISCUSSION

This study evaluated daily and chronic (i.e., 4-week) lnRMSSD responses to training among an elite college football team throughout Spring training camp. The primary finding was that lnRMSSD responses to a football training session differs by position. At lnRMSSDpost20, LINEMEN show substantial reductions from lnRMSSD_BL while SKILL and MID-SKILL were recovered to within or near baseline values. Additionally, lnRMSSDcv was inversely related to PL_chronic, independent of body mass.

The position \times time interaction observed in the current study indicates that ~20 h is insufficient for cardiac-parasympathetic activity to return to baseline for LINEMEN following a football practice. This occurred despite smaller PlayerLoadTM values for LINEMEN relative to SKILL and MID-SKILL (ES = *Very Large* and *Large*, respectively). This is most likely an effect of aerobic fitness level as athletes who are more fit show less cardiac-autonomic perturbation from exercise and accelerated lnRMSSD recovery to pre-exercise levels.¹² The *Large* inverse relationship ($r = -0.62, p < 0.01$) between $\Delta \ln \text{RMSSD}$ and body mass observed in the current study may further support this postulation given that body mass is inversely related to $\dot{V}O_{2\max}$ when expressed relative to body mass.⁴³ LINEMEN have both the highest body mass and lowest $\dot{V}O_{2\max}$ values of all positional groups.^{21,44} LINEMEN have also been reported to experience greater elevations in core temperature and greater fluid loss from perspiration during training relative to other positions, independent of metabolic heat production.⁴⁵ Therefore, alterations in fluid balance homeostasis not restored to pre-exercise values may also have contributed to the suppressed lnRMSSDpost20 in LINEMEN.

Whether unrecovered lnRMSSD effects performance or injury-risk in football players remains to be determined, particularly during preseason and in-season training where sessions are

held more frequently. Hypothetically, consistent inadequate recovery over time may lead to suppressed lnRMSSD over prolonged periods which has been related with high perceived fatigue, illness, and decrements in running performance.⁴⁶⁻⁴⁸ We speculate that LINEMEN may be at greater risk of inadequate recovery when training over several consecutive days based on their daily lnRMSSD responses to training. Future research evaluating cardiac-autonomic responses to more frequent training is needed to provide insight regarding adaptive responses in football players and how this may be reflected in lnRMSSD.

Both lower fitness levels and higher body fat percentage among linemen may contribute to the significant difference in lnRMSSD observed between SKILL and LINEMEN.⁴⁹ A previous study reported a *Large* inverse relationship ($r = -0.50, p < 0.01$) between body mass index and vagal-HRV in healthy adults.⁵⁰ Moreover, LINEMEN often display health characteristics associated with metabolic syndrome including excess body fat, hypertension, hypercholesterolemia and elevated inflammatory markers.⁵¹ In addition, greater adiposity has been associated with selective leptin resistance which attenuates its weight reducing effects while maintaining sympatho-excitatory activity.⁵² Future research is needed to investigate relationships between health status, neuroendocrine markers and vagal-HRV in LINEMEN.

Relationships between chronic training load and lnRMSSD parameters have not previously been investigated. While indirect, chronic training load is sometimes used as a surrogate for fitness level.²⁶ Previous studies have found that higher aerobic fitness is positively related with high intensity and total running distance in soccer players.^{53,54} We did not find a significant relationship between lnRMSSD_chronic and PL_chronic. This may be because changes in averaged lnRMSSD are more sensitive to fitness than chronic averages.^{46,55,56} A significant inverse relationship between lnRMSSDcv and PL_chronic was observed even after adjusting for body mass. This

indicates that the degree of fluctuation in lnRMSSD over 4-weeks appears to be a better predictor of training capacity than averaged lnRMSSD, independent of body mass. This aligns with previous investigations demonstrating that lnRMSSDcv is inversely related to $\dot{V}O_{2\max}$ and intermittent running performance in soccer players.^{23-25,46}

In practice, monitoring lnRMSSDcv along with training load in football players may provide insight regarding individual training status as previously demonstrated in sprint-swimmers and soccer players.^{42,46,47} For example, the lowest lnRMSSDcv among SKILL (Athlete A: 2.5%) was from a player who in addition to having the second highest PL_chronic and being a stand-out player, is regarded by sports medicine and nutrition staff as having a high commitment to lifestyle factors such as diet, sleep and recovery. In contrast, the highest lnRMSSDcv among SKILL (Athlete B: 11.6%) was from a player who had surgery in the preceding months and is regarded as having a more stressful lifestyle. This example may suggest that Athlete A was fit and tolerating training well based on his low lnRMSSDcv while Athlete B was experiencing greater homeostatic perturbations from training based on his high lnRMSSDcv. This is likely due to reduced fitness because of the recent medical procedure that prevented Athlete B from full participation in off-season training. From the daily analysis, Athlete B was the player experiencing the greatest reduction in lnRMSSDpost20 among SKILL (depicted in Figure 2.1b as the dashed line), further supporting the interpretation that fitness level is likely a key variable affecting lnRMSSD responses to training. Further research evaluating the evolution of lnRMSSDcv and training load with additional markers of fitness and recovery in football players is needed to explore the potential usefulness of these metrics used in combination.

The findings of this study must be considered with its limitations. While HRV data collection was standardized according to previous investigations,^{34,36,37} there is greater potential

for “noise” when acquired at the facility versus at home after waking. However, this method is more practical from a compliance perspective in a team environment, demonstrating greater ecological validity and application for sports-teams. Practitioners who adopt these methods are encouraged to strictly standardize procedures to limit noise and improve data quality. Another limitation is that HRV data were only collected on football training days and therefore the $\ln\text{RMSSD}_{\text{chronic}}$ and $\ln\text{RMSSD}_{\text{cv}}$ values do not reflect all days of the week. Recent studies have shown, however, that as few as three $\ln\text{RMSSD}$ recordings per week can still be used to meaningfully assess training responses in athletes.^{41,42} The small sample of LINEMEN is also a limitation and therefore these findings should be interpreted with caution. The $\ln\text{RMSSD}$ responses observed during this investigation may not reflect what occurs during training in hotter conditions with more frequent training sessions, such as during preseason training camp. Finally, markers of neuromuscular performance were not evaluated and may or may not respond in kind with $\ln\text{RMSSD}$.

CONCLUSION

In conclusion, the daily $\ln\text{RMSSD}$ response to a training session varies among positional groups and is largely related to body mass. ~Twenty hours of rest between training sessions does not appear adequate for complete cardiac-parasympathetic recovery among LINEMEN and among select individuals from other positional groups. Thus, $\ln\text{RMSSD}$ may be useful for monitoring individual training responses among football players during periods involving consecutive daily training sessions to avoid autonomic nervous system imbalance over prolonged periods. Moreover, developing a capacity for greater chronic workloads may be protective against daily perturbations

in cardiac-autonomic homeostasis based on the inverse relationship between PL_chronic and lnRMSSDcv.

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CHAPTER 3

HEART RATE VARIABILITY AND PSYCHOMETRIC RESPONSES TO PRESEASON TRAINING CAMP IN HOT AND HUMID CONDITIONS AMONG ELITE COLLEGE FOOTBALL PLAYERS

ABSTRACT

Preseason training camps in the heat are physiologically and psychologically taxing, placing athletes at risk of inadequate recovery. **PURPOSE:** To monitor daily heart rate variability (HRV) and psychometric responses (Wellness) to training among an elite college football team during a 13-day preseason camp in hot and humid conditions. **METHODS:** Vagal-related HRV (lnRMSSD) and Wellness were collected daily before training with a mobile application. Linear mixed models were used to examine variation in lnRMSSD and Wellness among and between positional groups (i.e., SKILL, MID-SKILL and LINEMEN) and across days. **RESULTS:** SKILL demonstrated *Small – Moderate* progressive increases in lnRMSSD from Days 3 – 8 with a *Large* peak on Day 12 after a day of passive rest. LINEMEN experienced a *Moderate* reduction in lnRMSSD on Day 2 and a *Large* peak on Day 12 following a day of passive rest. MID-SKILL demonstrated no meaningful changes in lnRMSSD throughout the 13-day training camp. *Small – Moderate* reductions in lnWellness throughout camp were observed with a return to Day 1 values among SKILL and LINEMEN following a day of passive rest (i.e., Day 12). lnWellness remained suppressed after Day 1 among MID-SKILL throughout the duration of training camp. **CONCLUSION:** Rather than decreasing, lnRMSSD progressively increased among SKILL and LINEMEN after the first few days of preseason camp. The lack of improvement in lnRMSSD and

InWellness in MID-SKILL after a day of passive rest suggests that they responded least favorably among positional groups. Heat acclimatization responses may attenuate typical fatigue-related decrements in InRMSSD.

INTRODUCTION

Preseason training camps for American college football programs consist of a highly-concentrated period of intensified training, often with two full-length practice sessions held on the same day. Preseason camps occur in late summer when high heat and humidity contribute to an increased risk of dehydration.¹ This is further exacerbated by players' large muscle mass and protective equipment requirements that limit heat loss, posing a substantial challenge to thermoregulation.¹ With an increase in both training load and heat stress, football players experience greater physiological perturbation² and an increased risk of injury during this time period.^{3,4} Therefore, monitoring training load along with perceptual and physiological responses in football players during preseason camps may be useful for evaluating how individuals are adapting to training. However, time constraints in the applied setting necessitates convenient, non-invasive measures that can be obtained frequently and with minimal burden to players. Thus, investigation into the usefulness of practical monitoring protocols among football players is needed.

Vagal-related heart rate variability (HRV) is an objective, non-invasive physiological marker that reflects cardiac-parasympathetic modulation and can be acquired conveniently with mobile applications.^{5,6} The autonomic nervous system plays a fundamental role in the recovery process from exercise by facilitating neuroendocrine signaling, clearance of metabolic by-products and restoring body temperature and fluid balance in an effort to reestablish homeostasis^{7,8}. Thus,

HRV is becoming a popular cardiovascular recovery status marker for monitoring athletes.⁷ Results from previous investigations indicate that reductions in resting-HRV are indicative of physiological stress⁹ and a maladaptive training response when chronically suppressed.^{10,11} In contrast, increased HRV in response to training has been associated with increases in fitness and perceived wellness.¹¹⁻¹³ Daily HRV changes throughout preseason training in team-sport athletes are highly individual¹⁴ and have been related to training load¹⁵ fitness changes¹⁶⁻¹⁹ and physiological adaptations such as changes in plasma volume.²⁰ Thus, HRV may be a useful tool for monitoring football players during preseason training, however no research among this population currently exists.

Wellness questionnaires are commonly used to assess perceptual fatigue and recovery status in athletes.²¹ Self-report measures can be easily administered to athletes electronically via smartphone applications.⁹ A recent study showed that collegiate football players report increases in perceived soreness and decrements in sleep quality, energy and overall wellness levels following competition.²² Factors such as sleep quality and psycho-social stress have also been shown to impact HRV.²³ Thus, it has been recommended that HRV data be interpreted alongside psychometric responses to facilitate interpretation.^{7,8}

Distinct positional differences exist within a football team, each with unique physical and performance characteristics to meet specific movement requirements on the field. For example, receivers and defensive backs (SKILL) have the smallest body mass, greatest aerobic fitness and cover the greatest distances during play.^{24,25} Linemen (LINEMEN) typically weigh in excess of 130 kg and consequently have the lowest aerobic fitness and cover the least distance during play.^{24,25} Finally, running backs, tight-ends and linebackers (MID-SKILL) display body mass, aerobic fitness and running distance requirements intermediate to that of SKILL and

LINEMEN.^{24,25} While fluid balance and thermoregulatory responses to training differ among positional groups,¹ it is reasonable to hypothesize that training status indicators may also differ by position. The purpose of this study was therefore to monitor daily HRV and psychometric responses to training among an elite collegiate football team as a group and by position during a preseason training camp in hot and humid conditions.

METHODS

Subjects

Twenty-eight collegiate football players from the National Collegiate Athletics Association's Southeastern Conference volunteered for this study. Subjects were categorized as SKILL (n = 11; age = 20.3 ± 1.3 years; height = 186.8 ± 3.9 cm; weight = 89.1 ± 5.3 kg), MID-SKILL (n = 9; age = 19.8 ± 1.5 years; height = 188.8 ± 5.8 cm; weight = 106.8 ± 7.5 kg) and LINEMEN (n = 8; age = 20.7 ± 1.4 years; height = 191.6 ± 5.3 cm; weight = 134.2 ± 9.8 kg) based on position as described previously.²⁶ All participating subjects were athletic scholarship players and ≥18 years of age. All subjects provided written informed consent and obtained medical clearance from the sports medicine staff for participation in football training. Ethical approval for this study was granted by the institutional review board for human participants.

Study Design

This was an observational cohort study where resting vagal-HRV, perceived wellness and microsensor-derived training load were acquired on each training day throughout a 13-day annual preseason training camp of an elite collegiate football team. The researchers did not influence the

training program or structure. Therefore, the methodology and timing of data collection were planned according to the schedule of the team.

Preseason Camp

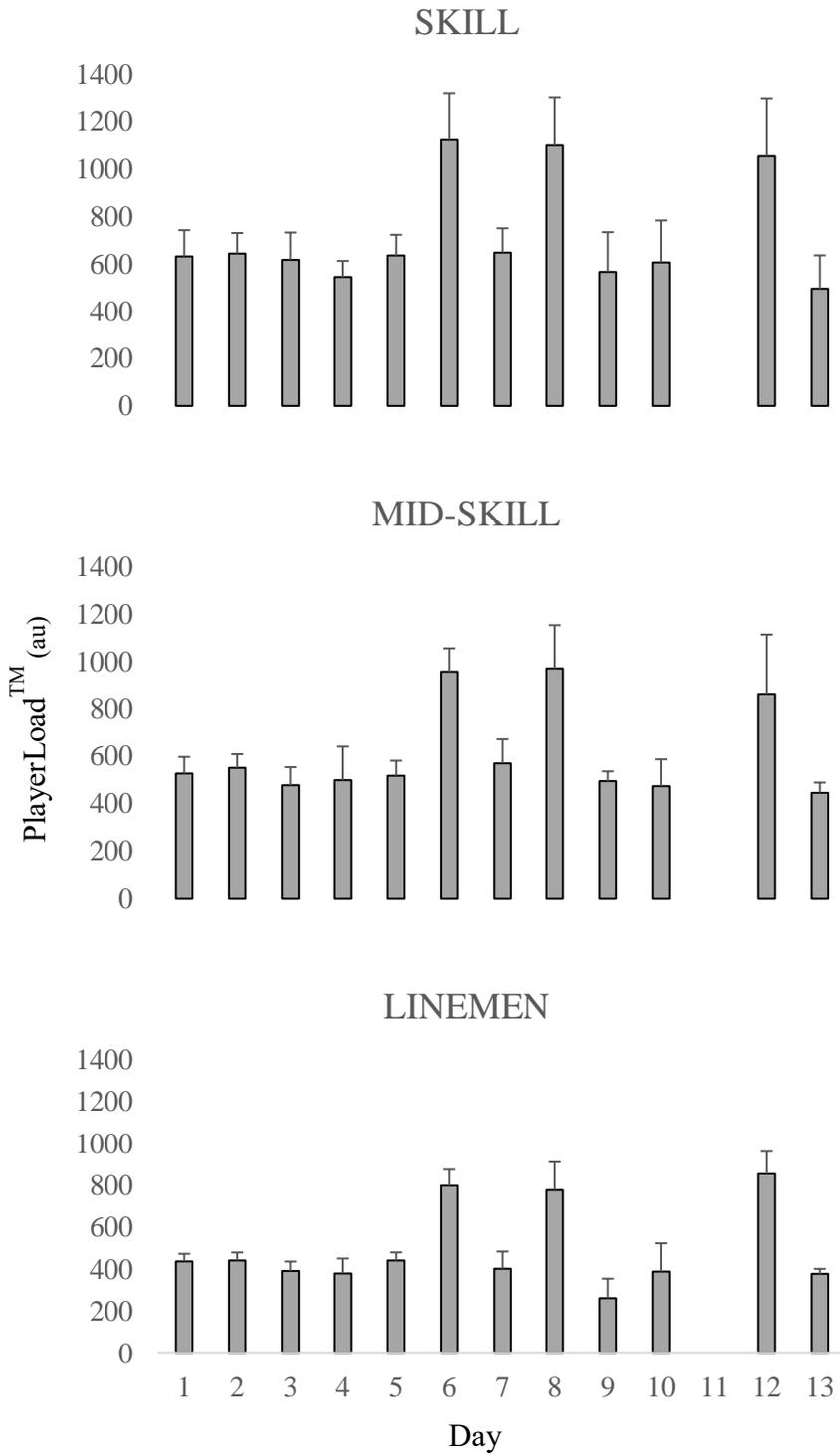
The preseason training camp was comprised of 15 football training sessions spread across 13 days beginning in early August of 2016. Two-a-day practices occurred 3 times on non-consecutive days (i.e., days 6, 8 and 12). Complete passive rest was provided on day 11. Football training sessions were 2 hours in duration and performed on natural grass on an outdoor field (n = 12 sessions) or on artificial field-turf indoors (n = 3 sessions). Average environmental conditions during outdoor training sessions throughout preseason camp were: temperature = 31.1 ± 4.2 °C; heat index = 38.1 ± 6.5 °C; relative humidity = $70.7 \pm 16.4\%$.

External Training Load

Movement parameters were obtained from each training session via 10 Hz GPS and integrated 100 Hz tri-axial accelerometer (minimaxX, Catapult Innovations, Melbourne, Australia). This device measures full-body accelerations in the posterior/anterior, medial lateral and vertical planes. All subjects wore the same microsensor for each training session, positioned between the scapulae, underneath their shoulder pads as described previously.²⁷ Training load data were downloaded to a laptop for analysis using specialized software (Catapult Innovations) following each training session. PlayerLoad™ was used to quantify training load for each session. PlayerLoad™ is accelerometer derived and reflects total external workload including running, jumping, changes of direction and body contacts, is reliable^{28,29} and has been used to quantify injury risk in college football players.²⁷ PlayerLoad™ is expressed as the square root of the sum

of the squared instantaneous rate of change in acceleration in each of the three vectors and divided by 100. Due to limited devices and preferential allocation to SKILL players by coaching staff, only data from 4 LINEMEN were obtained. PlayerLoadTM values by position are displayed in Figure 3.1.

Figure 3.1.



Daily PlayerLoad™ values reported in arbitrary units (au) by positional group throughout preseason training camp. Day 11 was reserved for passive rest.

Heart Rate Variability

HRV data were acquired 90-120 min following breakfast on each training day at the athletic training facility. HRV recordings were obtained while subjects were seated comfortably on an athletic training table prior to receiving treatment (e.g., ankle taping). Once seated, subjects were given a tablet device (iPad2, Apple Inc. Cupertino, California, USA) fitted with an optical pulse-wave finger sensor (PWFS) (HRV Fit LTD. Southampton, UK) inserted into the headphone slot. The PWFS detects pulse-rate via photo-plethysmography and has demonstrated acceptable agreement with electrocardiograph-derived HRV in previous comparisons.^{6,30} Subjects were verbally instructed to insert their left index finger into the PWFS, then to select their name from the team roster previously uploaded onto the iPad application (ithlete™, HRV Fit LTD. Southampton, UK) by a researcher. Following at least 1 min for stabilization,³¹ the subjects then initiated a supervised 1-min HRV measure while remaining quiet, still and breathing spontaneously. The application provides a time domain HRV index, the logarithm of the root mean square of successive R-R intervals which is multiplied by 20 (lnRMSSD) to fit an approximate 100-point scale for simplified interpretation.⁵ The lnRMSSD is the preferred HRV parameter for monitoring athletes in field settings for reasons described previously.⁸ The application is equipped with an irregular pulse-rate detection algorithm which excludes inter-pulse intervals <500 ms and >1800 ms.⁵ Ultra-short (i.e., 1-min) lnRMSSD recordings have been shown to suitably reflect traditional 5-min lnRMSSD measures in collegiate and professional athletes when obtained at the training facility following ~2 hours of fasting.³²⁻³⁴ In addition, seated, ultra-short lnRMSSD obtained in field settings has shown to provide acceptable intra- and inter-day reliability in professional collision-sport athletes³⁵ while also demonstrating sensitivity to training-induced

changes.³⁴ InRMSSD data were automatically uploaded from the tablet to a web-based interface for analysis.

Wellness Questionnaires

Following the HRV recording, a brief wellness questionnaire adapted from Mclean et al.³⁶ appeared on the tablet screen via the application. Using an electronic sliding scale, the subjects rated their perceived level of sleep quality, fatigue, muscle soreness, stress and mood on a 9-point scale. A rating of 5 represented feeling “okay” while ratings <5 were incrementally more negative and >5 were incrementally more positive. Upon completion, wellness data were automatically uploaded to the web-based interface for analysis. A single overall daily wellness score was used for analysis by averaging each category intra-individually.

Statistical Analysis

Data normality for HRV and Wellness residuals was assessed with the Shapiro-Wilk test. General linear mixed models were used to examine variation in InRMSSD and wellness among positions (i.e., SKILL, MID-SKILL and LINEMEN) and across days. Position was included as a fixed main effect, day as a fixed within-subjects repeated measure, the position × time interaction as a fixed main effect, and athlete identification as a random effect. In addition, we evaluated the magnitude of differences among variables with Cohen’s *d* effect sizes (ES) ± 90% confidence limits (CL).³⁷ ES were interpreted qualitatively as follows: <0.2, trivial; 0.2–0.59, small; 0.6–1.19, moderate; 1.2–1.9, large; >2.0, very large. The effect was deemed unclear if the 90% CL overlapped both substantially positive and negative values (i.e., 0.2 and -0.2).

RESULTS

A significant position \times day interaction was observed for lnRMSSD ($F_{22,275} = 1.79$; $p = 0.018$). Mean \pm standard deviation values by position and as a group are included in Table 3.1a. Tukey HSD post-hoc analysis showed that there were no statistically significant differences in lnRMSSD across time for SKILL. However, when compared to Day 1, ES analysis demonstrated *Small to Moderate* increases in lnRMSSD on Day 3 – 8 with a *Large* peak on Day 12 following a day of passive rest (Figure 3.2). Tukey HSD post-hoc analysis showed that there were no statistically significant differences in lnRMSSD across time for MID-SKILL ($p < 0.05$) and ES were each deemed *Unclear* (Figure 3.2). Tukey HSD post-hoc analysis showed that lnRMSSD on Day 7 was significantly greater than that on Day 2 while Day 12 was significantly greater than that on Days 1-5, 9 and 10 for LINEMEN ($p < 0.05$). When compared to Day 1, ES analysis showed a *Moderate* decrease in lnRMSSD on Day 2 and a *Large* increase in lnRMSSD on Day 12 following a day of passive rest (Figure 3.2).

Table 3.1. Daily mean and standard deviation for natural logarithm of the root mean square of successive R-R interval differences (lnRMSSD) (a.) and natural logarithm of Wellness (lnWellness) (b.) throughout preseason training camp.

a. lnRMSSD

	SKILL	MID-SKILL	LINEMEN	Group (n = 28)
Day 1	80.4 ± 7.0	80.2 ± 10.8	79.1 ± 10.0	80.0 ± 8.9
Day 2	81.7 ± 8.1	78.3 ± 13.2	71.6 ± 11.2	77.7 ± 11.2
Day 3	85.6 ± 6.7	77.4 ± 9.6	75.4 ± 10.2	80.1 ± 9.6
Day 4	85.4 ± 9.7	81.9 ± 9.2	77.2 ± 10.9	82.0 ± 10.1
Day 5	84.5 ± 4.4	80.2 ± 10.6	77.6 ± 7.1	81.2 ± 7.9
Day 6	84.0 ± 10.9	77.8 ± 10.5	81.9 ± 8.1	81.4 ± 10.0
Day 7	87.4 ± 8.6	80.8 ± 12.3	83.7 ± 8.4 [€]	84.2 ± 9.9
Day 8	85.1 ± 8.5	78.0 ± 12.6	80.0 ± 12.3	81.4 ± 11.1
Day 9	83.3 ± 9.3	80.7 ± 10.4	76.9 ± 10.6	80.6 ± 10.0
Day 10	82.3 ± 7.7	79.0 ± 9.5	78.4 ± 7.5	80.1 ± 8.2
Day 11	-	-	-	-
Day 12	88.4 ± 6.2	81.2 ± 9.5	89.8 ± 7.1 [*]	86.5 ± 8.2 [¥]
Day 13	83.2 ± 7.6	80.0 ± 9.4	81.6 ± 6.3	81.7 ± 7.7

* = significantly greater than Day 1-5, 9 and 10 ($p < 0.05$); [€] = significantly greater than day 2 ($p < 0.05$); [¥] = significantly greater than all other days ($p < 0.05$).

b. lnWellness

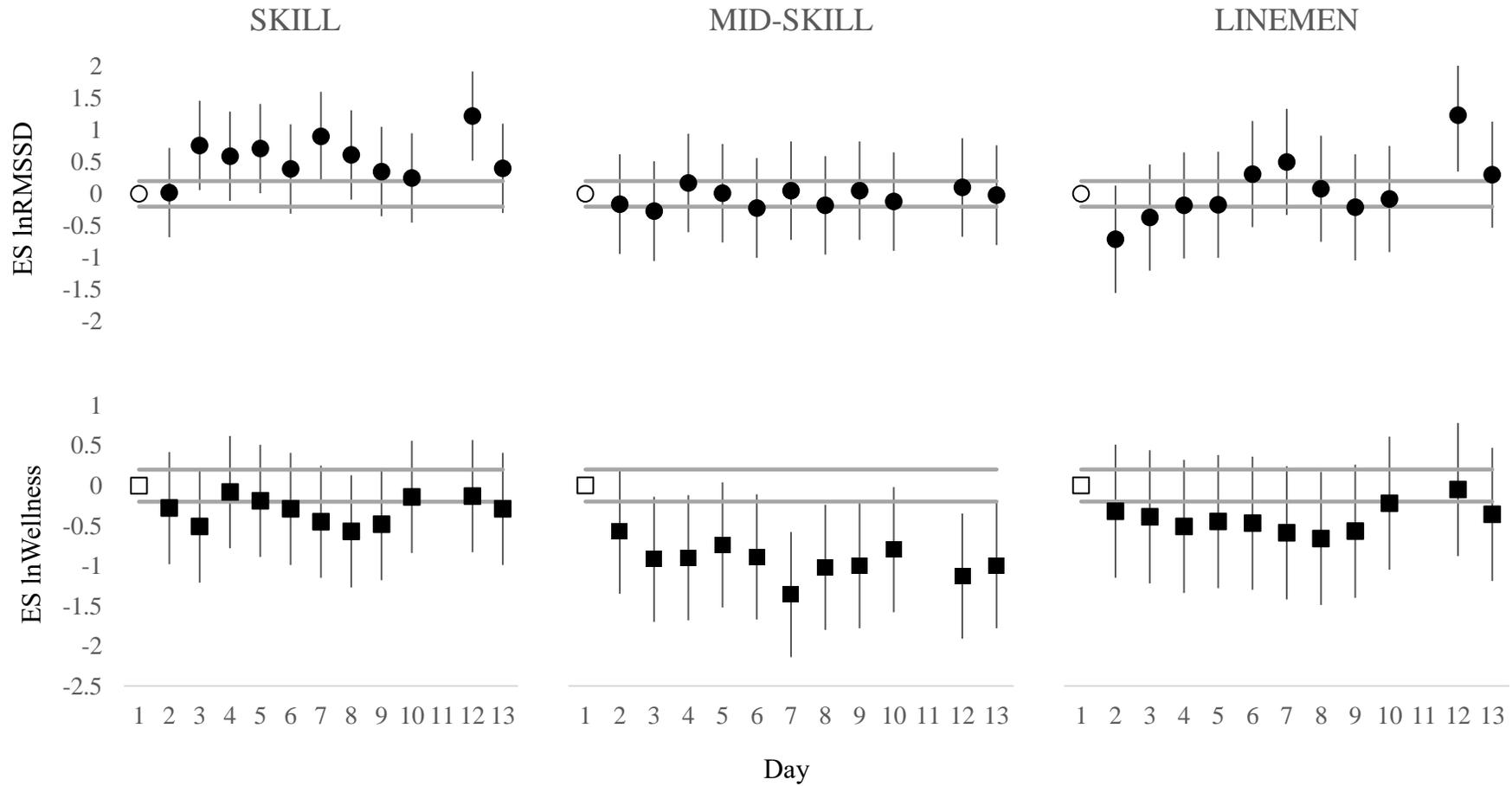
	SKILL	MID-SKILL	LINEMEN	Group (n = 28)
Day 1	1.85 ± 0.23	1.98 ± 0.20	1.99 ± 0.19	1.93 ± 0.22 [¥]
Day 2	1.78 ± 0.27	1.86 ± 0.21	1.92 ± 0.25	1.84 ± 0.25
Day 3	1.74 ± 0.20	1.81 ± 0.17	1.90 ± 0.27	1.81 ± 0.22
Day 4	1.83 ± 0.25	1.80 ± 0.20	1.88 ± 0.24	1.83 ± 0.23
Day 5	1.81 ± 0.19	1.84 ± 0.18	1.89 ± 0.26	1.84 ± 0.20
Day 6	1.79 ± 0.18	1.81 ± 0.17	1.88 ± 0.27	1.82 ± 0.21
Day 7	1.73 ± 0.30	1.75 ± 0.15	1.86 ± 0.25	1.77 ± 0.24
Day 8	1.71 ± 0.26	1.80 ± 0.15	1.84 ± 0.22	1.77 ± 0.22
Day 9	1.74 ± 0.23	1.77 ± 0.22	1.87 ± 0.23	1.79 ± 0.23
Day 10	1.82 ± 0.21	1.82 ± 0.20	1.95 ± 0.17	1.85 ± 0.20
Day 11	-	-	-	-
Day 12	1.82 ± 0.23	1.73 ± 0.25	1.98 ± 0.18	1.84 ± 0.24
Day 13	1.78 ± 0.25	1.77 ± 0.22	1.92 ± 0.19	1.82 ± 0.22

¥ = Significantly greater than all other days except Day 10 ($p < 0.05$).

A significant main effect for Day was observed $F_{11,275} = 4.90$; $p < 0.0001$. Tukey HSD post-hoc analysis showed that lnRMSSD from Day 7 and Day 12 were significantly greater than Day 2 ($p < 0.05$). ES analysis showed that compared to Day 1, increases in lnRMSSD were *Small* and *Moderate* on Day's 7 and 12, respectively. There was no significant main effect for Position ($F_{2,25} = 1.26$; $p = 0.302$), although ES showed *Small* differences ($ES \pm 90\% CL = 0.52 \pm 0.50$) in lnRMSSD between SKILL (84.3 ± 8.0) and MID-SKILL (79.6 ± 10.3) and *Small* differences ($ES \pm 90\% CL = 0.56 \pm 0.54$) between SKILL and LINEMEN (79.4 ± 9.8).

Wellness data violated the assumption of normality ($p < 0.001$) and therefore natural logarithmic transformations were applied (ln). A significant main effect for Day was observed ($F_{11,275} = 6.14$; $p < 0.001$). lnWellness on Day 1 was significantly greater than all other days except Day 10 (all $p < 0.05$) (Table 3.1b). ES analysis showed that compared to Day 1, all subsequent days showed *Small – Moderate* decreases in lnWellness (Figure 3.2). There was no significant position \times day interaction ($F_{22,275} = 1.38$; $p = 0.123$). ES analysis showed that reductions in lnWellness ranged from *Unclear – Small* for SKILL, *Unclear – Large* for MID-SKILL and *Unclear – Small* for LINEMEN (Figure 3.2). No significant main effect was observed for position ($F_{2,25} = 0.935$; $p = 0.406$).

Figure 3.2.



Effect size (ES) \pm 90% confidence limits for daily natural logarithm of the root mean square of successive R-R interval differences (lnRMSSD) and lnWellness throughout pre-season training camp. The horizontal grey lines represent thresholds for a small effect (0.2 - -0.2). Effect sizes were calculated by comparing each day to Day 1.

DISCUSSION

This study evaluated daily lnRMSSD and Wellness responses throughout a preseason training camp in hot and humid conditions among an elite college football team. The main finding was the significant position \times day interaction for lnRMSSD. SKILL demonstrated *Small – Moderate* progressive increases in lnRMSSD from Days 3 – 8 with a *Large* peak on Day 12 after a day of passive rest. LINEMEN experienced a *Moderate* reduction in lnRMSSD on Day 2 and a *Large* peak on Day 12 following a day of passive rest. MID-SKILL demonstrated no meaningful changes in lnRMSSD throughout the 13-day training camp. While the position \times day interaction for lnWellness was not statistically significant, *Small – Moderate* reductions in lnWellness throughout camp were observed with a return to Day 1 values among SKILL and LINEMEN following a day of passive rest (i.e., Day 12). lnWellness remained suppressed after Day 1 among MID-SKILL throughout the duration of training camp.

Intensive training periods are typically associated with reductions in cardiac-parasympathetic activity and decrements in perceived Wellness.^{11,38,39} Only LINEMEN demonstrated a *Moderate* decrease in lnRMSSD on Day 2 following the first day of intensive training in the heat. This is likely explained by fitness level as LINEMEN are the least aerobically fit positional group in football²⁵ and recovery of lnRMSSD to pre-exercise levels takes longer in individuals who are less fit.⁷ SKILL and MID-SKILL showed no substantial lnRMSSD change after Day 1, possibly due to superior fitness levels relative to linemen²⁵ facilitating faster cardiac-parasympathetic recovery following training.⁷ After Day 2, a progressive increase in lnRMSSD among LINEMEN with *Small* increases above Day 1 values on Days 6 and 7 was observed, though the ES were deemed *Unclear* due to the overlap of the 90% CL (Figure 3.2). The increase in lnRMSSD occurred despite a progressive reduction in lnWellness until Day 8. Among SKILL,

lnRMSSD showed *Small–Moderate* increases above Day 1 from Day 3–8. Similar to LINEMEN, these increases in lnRMSSD occurred despite *Small* reductions in lnWellness.

While reduced lnRMSSD is an expected response to high intensity training periods,⁷ it has been suggested that hot environmental conditions may cause increases rather than decreases in lnRMSSD.⁸ For example, Buchheit reported an initial reduction followed by a progressive increase in lnRMSSD above baseline values that peaked on Day 7 among 6 runners competing in the “Marathon des Sables” over a one-week period in temperatures that exceeded 50 °C.⁸ This occurred despite increases in perceived fatigue among the runners.⁸ The increase in lnRMSSD observed by Buchheit was attributed to changes in plasma volume as a result of exercise-induced hypervolemia and heat acclimatization responses.⁸ In support of this assessment, a previous investigation found that both plasma volume and RMSSD significantly increased above baseline 48 hours after intense training. The change in plasma volume correlated with changes in RMSSD ($r = 0.85$). Another investigation involving elite Australian football players during a training camp in the heat reported progressive increases in both vagal-related HRV and plasma volume.²⁰ Moreover, acclimatization responses to training in the heat have been shown to increase plasma volume by 12% within 3 days and 23% within 6-10 days as a result of increased vascular plasma protein content.⁴⁰ The increase in RMSSD associated with plasma volume expansion is thought to be mediated by stimulation of cardiopulmonary and arterial baroreceptors that signal for inhibition of sympathetic and excitation of parasympathetic efferent outflow to augment pressure changes.^{41,42}

Both LINEMEN and SKILL experienced peak lnRMSSD values on Day 12 following a day of passive rest. This response was associated with lnWellness that returned to Day 1 values and thus is interpreted as a positive response. However, it is unclear if the peak in lnRMSSD was

a result of expansion of plasma volume or if the day of passive rest contributed to a heightened vagal response to facilitate recovery processes. Interestingly, MID-SKILL did not experience any substantial change in lnRMSSD and their lnWellness values further regressed after a day of passive rest. This may suggest that MID-SKILL were adapting less-favorably to the training camp relative to SKILL and LINEMEN.¹²

Taken with previous findings, it seems that during intensive training periods in the heat, increases in plasma volume may counteract the expected fatigue-related decrements in lnRMSSD beyond the first few days. Since this occurred concurrently with decrements in lnWellness, practitioners must use caution when interpreting training status from lnRMSSD given that increases in lnRMSSD are sometimes used to support prescription of intensive training.⁴³ Alternatively, these data may suggest that the increase in lnRMSSD was reflecting positive physiological adaptation (e.g., heat acclimatization), despite reduced Wellness. This assertion is based on the lack of increase in lnRMSSD observed in MID-SKILL and chronic suppression of lnWellness that worsened, rather than improved after a day of passive rest. Hypothetically, an increase in lnRMSSD during training in the heat may therefore be a desirable physiological response. Greater plasma volume enhances myocardial efficiency via enhanced venous return and increased stroke volume, facilitating cardiac output and oxygen delivery at a lower heart rate for a fixed level of exercise intensity.⁴⁴ Additionally, the elevated plasma volume supports thermoregulatory responses and reduces cardiac strain during exercise in the heat.⁴² However, this contention is speculative given that plasma volume was not measured in the current study.

A limitation of the present study is that markers of fitness, performance and hydration status among these subjects were not measured. These should be included in future studies to improve interpretation of lnRMSSD changes during intense training periods in the heat. Another

limitation is that lnRMSSD and lnWellness was acquired approximately 2.5 hours earlier on Day's 6, 8 and 12 due to the earlier training time to accommodate two practice sessions within one day. Finally, subjects were not accessible for acquisition of baseline lnRMSSD and is another limitation of the current study.

CONCLUSION

To conclude, after the first few days of training in the heat, decrements in lnWellness and increases in lnRMSSD that peaked on Day 12 following a day of passive rest among SKILL and LINEMEN was observed. The peak in lnRMSSD was associated with the return of lnWellness to Day 1 values. MID-SKILL showed no meaningful changes in lnRMSSD and lnWellness remained chronically suppressed. Thus, heat acclimatization responses may attenuate the expected fatigue-related decrements in cardiac-parasympathetic activity during intensive training periods.

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CHAPTER 4

HEART RATE VARIABILITY RESPONSES TO IN-SEASON TRAINING AMONG ELITE COLLEGE FOOTBALL PLAYERS

ABSTRACT

Despite having to endure a rigorous in-season training schedule, research evaluating daily recovery status markers among American football players is limited. **PURPOSE:** The purpose of this study was to evaluate heart rate variability responses to in-season training among an elite American collegiate football team. **METHODS:** Twenty-nine starters or starting back-ups were divided into groups based on position as follows: receivers and defensive backs (SKILL, $n = 10$); running backs, linebackers and tight-ends (MID-SKILL, $n = 11$) and linemen (LINEMEN, $n = 8$). On three occasions during the first month of the competitive season, the natural logarithm of the root mean square of successive R-R interval differences ($\ln\text{RMSSD}$) was measured before ($\ln\text{RMSSD}_{\text{pre}}$) and 20 h following ($\ln\text{RMSSD}_{\text{post20}}$) the heaviest training session of the week. Training load was quantified via PlayerLoadTM. Data were analyzed using linear mixed models and effect sizes \pm 90% confidence limits ($\text{ES} \pm 90\% \text{ CL}$). **RESULTS:** A significant position \times time interaction was observed for $\ln\text{RMSSD}$. Differences in $\ln\text{RMSSD}_{\text{pre}}$ and $\ln\text{RMSSD}_{\text{post20}}$ for SKILL were not statistically significant. $\ln\text{RMSSD}_{\text{pre}}$ was significantly greater than $\ln\text{RMSSD}_{\text{post20}}$ for MID-SKILL and LINEMEN. Average delta changes in $\ln\text{RMSSD}$ ($\ln\text{RMSSD}_{\text{post20}} - \ln\text{RMSSD}_{\text{pre}}$) significantly related with PlayerLoadTM and body mass. **CONCLUSION:** After 20 h of recovery following an intense in-season training session, $\ln\text{RMSSD}$ did not return to pre-training values for

LINEMEN or to a lesser extent, MID-SKILL. Greater reductions in lnRMSSD tended to occur in players with larger body mass and lower PlayerLoad™, though some individual variability was observed.

INTRODUCTION

Training sessions for American college football teams are typically two hours in duration and involve intense, intermittent bouts of sprinting, rapid changes of direction and physical contact such as blocking and tackling.¹ In addition to these physical demands, the large body mass of players combined with protective equipment requirements and hot environmental conditions add further physiological strain via added heat stress and increased fluid loss.² With football training sessions typically held on consecutive days during the competitive season, the potential for inadequate recovery between sessions may be heightened. However, the day-to-day recovery of football players during in-season training is not well studied.

Intense exercise such as football training challenges the cardiovascular system with delivering oxygen to active peripheral muscle tissue, facilitating lactate and metabolite clearance and functioning in thermoregulation.³ Cardiovascular adjustments during and after exercise are mediated centrally by the autonomic nervous system.⁴ Cardiac-autonomic activity can be assessed non-invasively via heart rate variability (HRV). Vagal-related HRV parameters are often used to monitor cardiovascular recovery status among athletes.⁵ The recommended approach to HRV monitoring in the field is to perform daily HRV recordings under resting conditions.⁵⁻⁷ The return of HRV to resting levels following a training bout is thought to reflect restoration of cardiovascular homeostasis.^{4,6} Planning training when resting-HRV is recovered to baseline levels may be superior to traditional, pre-planned training methods for inducing performance-related

cardiovascular adaptations.^{8,9} Conversely, sustained reductions in HRV have been associated with maladaptive training responses.^{10,11} Given the high cardiovascular stress that players experience from football training,¹² investigation into the usefulness of daily HRV as a recovery status metric for football players is warranted.

Factors that affect cardiac-autonomic recovery after a training session include exercise intensity, fluid balance and fitness level.⁶ For example, elevated lactate and metabolite concentrations from anaerobic exercise activates the metaboreflex which in turn increases sympathetic-mediated increases in plasma catecholamine, prolonging acute cardiac-parasympathetic reactivation following exercise.^{6,13,14} Daily recovery of cardiac-parasympathetic activity appears to be related to restoration of fluid balance and plasma volume.¹⁵ Individuals with greater aerobic fitness exhibit less homeostatic perturbations from exercise and demonstrate accelerated cardiovascular recovery from training relative to individuals with lower aerobic fitness.¹⁶ Football players vary in size and fitness level based on playing position¹⁷ and are routinely exposed to high intensity exercise that can involve drastic increases in core temperature and fluid loss.¹⁸ For example, football linemen weigh in excess of 130 kg, display the lowest aerobic fitness¹⁷ and experience the greatest fluid loss from training.¹⁹ Non-linemen are smaller and more aerobically fit, but are exposed to greater running distances.^{17,20} Thus, complete restoration of cardiac-parasympathetic activity may differ among football players due to anthropometry, fitness and movement demands. However, this hypothesis has yet to be investigated. This research is needed because despite differing in size, fitness and responses to training,¹⁹ all positional groups are exposed to the same in-season training schedule which may not provide adequate recovery for all positions.^{17,19}

Markers of training and recovery status currently used by collegiate American football teams include subjective ratings of recovery via athlete self-report measures (ASRM)²¹ and external training load quantification via microtechnology.^{20,22,23} Subjective measures from wellness questionnaires provide insight regarding perceptual responses of players and have been shown to reflect the effects of football competitions on perceived soreness, energy and overall wellness.²¹ Further, it has been recommended that HRV be taken alongside other markers of recovery such as ASRM to add context to data interpretation.⁵ Wearable microtechnology (i.e., global positioning systems and tri-axial accelerometers) may add further context by providing information regarding training dose and indication of fitness level²⁴ as athletes with greater aerobic fitness accumulate greater running distances.^{25,26}

While the topic of recovery monitoring in athletes is receiving considerable attention in recent research,²⁷ American football players are a largely understudied group whose unique physical and performance characteristics make them an at-risk population for inadequate recovery. The purpose of this study was therefore to assess the daily HRV response to intense in-season football training among elite American college football players. An additional aim was to evaluate how body mass and training load relate with HRV responses.

METHODS

Subjects

Subjects were recruited from an elite Division 1A National Collegiate Athletic Association football team (n = 29). All subjects were athletic scholarship players and received regular competition playing time as a starter or starting back-up. The subjects were grouped based on playing position¹ due to similarities in physical and performance characteristics as follows:

receivers and defensive backs (SKILL: $n = 10$; age = 20.2 ± 1.3 years; height = 188.0 ± 4.1 cm; weight = 90.3 ± 6.0 kg), linebackers, running backs and tight-ends (MID-SKILL: $n = 11$; age = 19.7 ± 1.5 years; height = 187.5 ± 7.0 cm; weight = 103.1 ± 7.1 kg) and linemen (LINEMEN: $n = 8$; age = 20.4 ± 1.5 years; height = 191.6 ± 5.3 cm; weight = 135.0 ± 8.0 kg). All subjects were >18 years of age. Ethics approval for this study was granted by the institutional review board for human subject's research. All subjects provided written informed consent prior to participation.

Study Design

Data collection took place during the first month of the 2016 competitive football season (i.e., September). Standardized for time and location, vagally-mediated HRV and ASRM were acquired at rest prior to the most intense training session of the week and again approximately 20 h post-training at the same time and location. Data collection procedures were repeated over three weeks resulting in three separate pre- and 20-h post-training measures for each subject. Differences in mean pre- and 20-h post-training HRV and ASRM were assessed across all subjects combined and between positional groups. Relationships between body mass, microsensor-derived training load and the delta change in HRV were subsequently quantified.

Training Schedule

Weekly competition occurred each Saturday with passive rest or light training on Sunday and Monday. Football training sessions occurred on Tuesday through Friday with intensity and duration peaking on Tuesday and tapering progressively thereafter. Tuesday therefore represented the optimal day to acquire resting HRV that was least affected from previous high intensity training (e.g., 72 h post-competition).⁶ HRV and ASRM were acquired on Tuesday, 2-3 hours prior to

training and again the subsequent day (i.e., Wednesday) at the same time and location. Tuesday practices were approximately 2 hours in duration and included position-specific drills, technical and tactical training and scrimmaging. Full protective equipment was worn by the subjects for each Tuesday session allowing for live tackling and blocking.

Body Mass

During the week preceding regular season play, body mass was measured to the nearest 0.10 kg for each subject on a calibrated digital scale (Tanita Corporation, Illinois, USA) before breakfast at the football training facility in team-issued t-shirt and shorts. Prior to being weighed, subjects removed shoes and emptied pockets.

Heart Rate Variability

To facilitate consistent data acquisition from a large sample, HRV data was acquired at the football facility in the athletic training room. While seated comfortably on an athletic training table, subjects were provided with a tablet device (iPad2, Apple Inc. Cupertino, CA, USA) and optical pulse-wave finger sensor (PWFS) inserted into the headphone slot (HRV Fit LTD. Southampton, UK). Subjects inserted their left index finger into the PWFS and then selected their name from the team roster displayed on the mobile application (ithlete™ Team, HRV Fit LTD.) to initiate the HRV recording procedure. These tools demonstrate acceptable agreement with electrocardiography for calculating the vagally-mediated HRV parameter, i.e., the logarithm of the root mean square of successive R-R interval differences (lnRMSSD)^{28,29} and have been used in previous training studies.^{11,30} lnRMSSD is the preferred HRV parameter for athlete monitoring in field conditions.⁵ Pulse rate was recorded for 1-min to establish ultra-short-term lnRMSSD while

subjects remained quiet, still and breathed naturally.³¹⁻³³ All lnRMSSD recordings were preceded by at least 1-min for stabilization.³⁴ The mobile application uses a processing algorithm to filter ectopic beats and artifacts using inter-beat interval threshold values of <500 ms or >1800 ms for automatic correction.³⁵ The lnRMSSD value is multiplied by 20 to fit an approximate 100-point scale for simplified interpretation.³⁵ Ultra-short-term lnRMSSD has shown acceptable relative and absolute inter-day reliability in collision-sport athletes³⁶ and sensitivity to training-induced changes when obtained at the training facility.³⁷ All lnRMSSD measures were supervised by an investigator. Subjects were asked to refrain from caffeine consumption after waking to which they provided verbal confirmation before each HRV recording. All HRV measures were obtained at least 2 hours following breakfast and before lunch. HRV data were automatically uploaded to a web-based platform for analysis by the researcher.

Psychometrics

On a 9-point electronic sliding scale, subjects rated their perceived levels of sleep quality, fatigue, muscle soreness, stress and mood on the tablet device following their HRV recording. This wellness survey was adapted from Mclean et al.³⁸ A rating of 5 represented feeling “okay”, 6-9 represented more positive and 1-4 represented more negative ratings for a given parameter. Upon completion, questionnaire data were automatically uploaded to the web-based platform for analysis. A single wellness parameter (Wellness) was calculated for each subject by averaging their ratings from each category.

Training Load

External training load was quantified via tri-axial accelerometer (minimaxX, Catapult Innovations, Melbourne, Australia) using a sampling rate of 100 Hz. This device measures full-body acceleration in three planes: posterior/anterior, medial/lateral and vertical. Subjects wore the same device for each practice session, positioned between the scapulae, fixed in place on their shoulder pad in a custom-built cartridge. Following each practice session, training load data were downloaded to a laptop for analysis using accompanying software. The training load parameter used for this study was PlayerLoad™. This parameter reflects total external workload including running, jumping, changes of direction and body contacts and has been used previously to quantify injury-risk in college football players.²³ PlayerLoad™ has been demonstrated to be a reliable metric for tracking physical activity in team-sports.³⁹

Statistical Analysis

Data were screened for normality via the Shapiro-Wilk test. Natural logarithm (ln) transformations were applied to non-normal data to satisfy criteria for parametric procedures. A one-way ANOVA with Tukey HSD post-hoc analysis was used to compare Tuesday mean PlayerLoad™ values among positions. A general linear mixed model was used to examine variation in lnRMSSD among positions (i.e., SKILL, MID-SKILL and LINEMEN) and between lnRMSSD acquired prior to intense training (lnRMSSDpre) and lnRMSSD acquired 20 h post-training (lnRMSSDpost20). Position was included as a fixed main effect, time (lnRMSSDpre vs. lnRMSSDpost20) as a fixed within-subjects repeated measure, the position × time interaction as a fixed main effect, and athlete identification as a random effect. The same statistical procedure was used to examine variation in Wellness among positional groups and between pre-training wellness

(Wellness_pre) and Wellness obtained 20 h post-training (Wellness_post20). Post hoc analyses were performed using Tukey HSD comparisons. Cohen's d effect sizes (ES)⁴⁰ \pm 90% confidence limits (CL) were calculated to explore the magnitude of the differences for lnRMSSD and Wellness values. ES were interpreted qualitatively as follows: <0.2 , trivial; 0.2 – 0.59 , small; 0.6 – 1.19 , moderate; 1.2 – 1.9 , large; >2.0 , very large.⁴¹ The effect was deemed unclear if the CL crossed the threshold for both substantially positive (0.20) and negative (-0.20) values.⁴²

Delta change variables were calculated for lnRMSSD (i.e., $\ln\text{RMSSD}_{\text{post20}} - \ln\text{RMSSD}_{\text{pre}}$, $\Delta\ln\text{RMSSD}$) and averaged intra-individually across the three time points. Relationships between $\Delta\ln\text{RMSSD}$, body mass, and PlayerLoadTM were quantified with Pearson correlations. The thresholds used for qualitative assessment of the correlations were: <0.1 , trivial; 0.1 – 0.29 , small; 0.3 – 0.49 , moderate; 0.5 – 0.7 , large; 0.7 – 0.89 , very large; >0.9 nearly perfect.⁴¹ Statistical procedures were carried out using JMP Pro 13 (SAS Institute Inc. Cary, North Carolina, USA) and Excel 2016 (Microsoft Corp. Redmond, Washington, USA). Data are reported as mean \pm SD unless noted otherwise.

RESULTS

A significant effect was found for PlayerLoadTM values among positions ($F_{2, 78} = 21.97$; $p < 0.0001$). PlayerLoadTM values for SKILL, MID-SKILL and LINEMEN were 523.9 ± 76.9 au, 444.7 ± 74.8 au and 389.8 ± 47.0 au, respectively. Tukey HSD post-hoc analysis revealed that PlayerLoadTM for SKILL was significantly greater than MID-SKILL ($p = <0.0001$; ES \pm 90% CL = 1.49 ± 0.44 , *Large*) and LINEMEN ($p = <0.0001$; ES \pm 90% CL = 1.99 ± 0.47 , *Large*). Additionally, PlayerLoadTM for MID-SKILL was significantly greater than LINEMEN ($p = 0.026$; ES \pm 90% CL = 0.83 ± 0.49 , *Moderate*).

A significant position \times time interaction was observed for lnRMSSD (Table 4.1a.). Tukey HSD post-hoc analysis revealed that lnRMSSDpre was not significantly different from lnRMSSDpost20 for SKILL ($p = 0.346$; $ES \pm 90\% CL = -0.10 \pm 0.42$, *Unclear*). For MID-SKILL ($p < 0.05$; $ES \pm 90\% CL = -0.32 \pm 0.40$, *Small*) and LINEMEN ($p < 0.05$; $ES \pm 90\% CL = -0.44 \pm 0.48$, *Small*), lnRMSSDpost20 was significantly lower than lnRMSSDpre. Interaction plots are displayed in Figure 4.1a. A significant main effect for lnRMSSD by day was also observed (Table 4.1a.). Evaluated as all groups combined ($n = 29$), lnRMSSDpre was significantly greater than lnRMSSDpost20 ($p < 0.05$; $ES \pm 90\% CL = -0.28 \pm 0.26$, *Small*).

Table 4.1. Model effects and mean and standard deviation for the natural logarithm of the root mean square of successive R-R interval differences (lnRMSSD) (a.) and Wellness (lnWellness) (b.).

a. lnRMSSD

Model effect	F	df	P	Mean ± SD lnRMSSD		
Position	1.08	2, 26	0.353	Skill: 82.4 ± 8.9	Mid-Skill: 77.7 ± 9.5	Lineman: 76.9 ± 11.2
Day	24.88	1,26	<0.0001	BL: 80.5 ± 9.7	Post: 77.7 ± 10.2*	
Position × Time	3.69	2, 26	0.039	SKILL Pre: 82.8 ± 9.3 SKILL Post: 81.9 ± 8.7	MID-SKILL Pre: 79.2 ± 9.4 MID-SKILL Post: 76.2 ± 9.5*	LINEMAN Pre: 79.4 ± 10.5 LINEMAN Post: 74.5 ± 11.5*

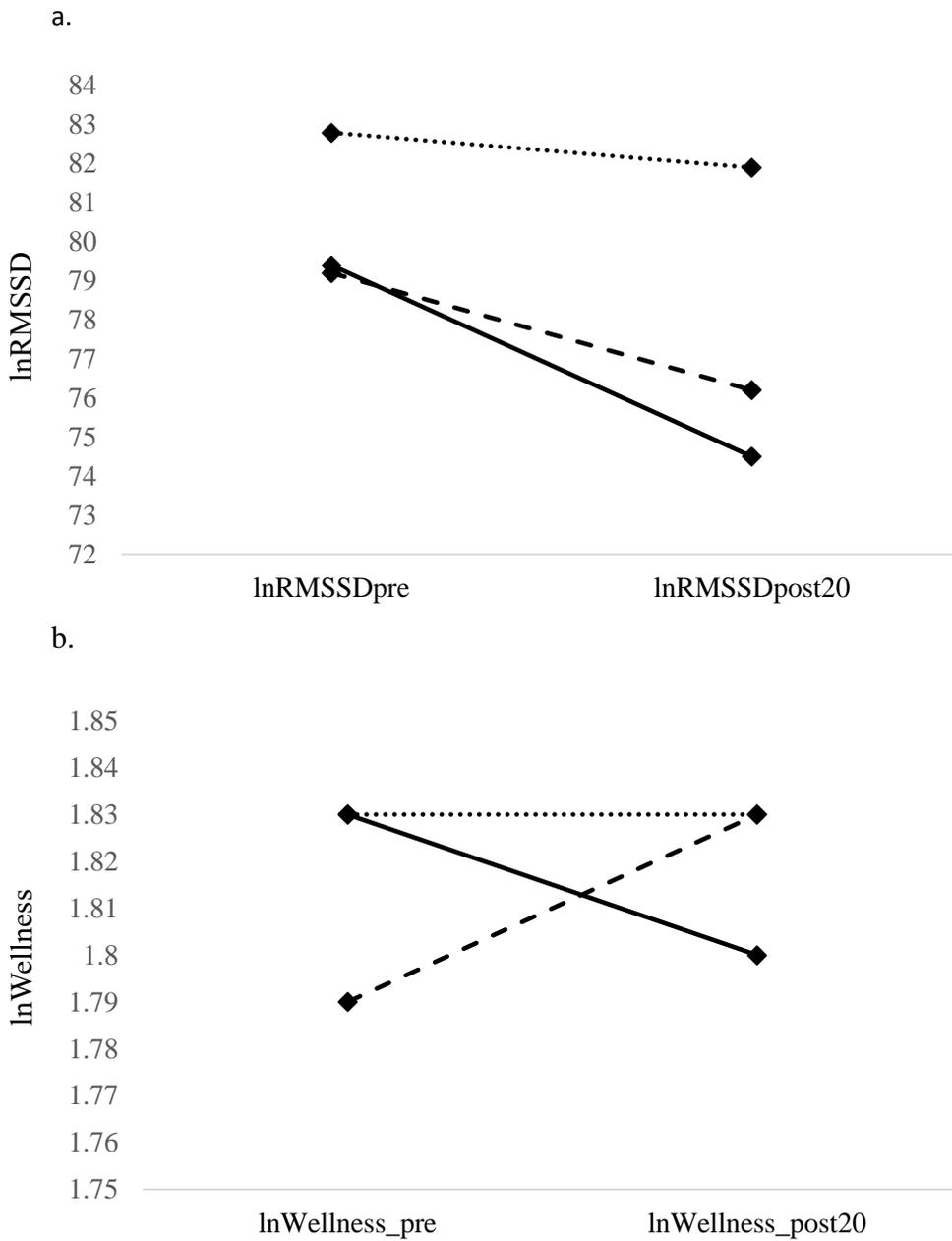
b. lnWellness

Model effect	F	df	P	Mean ± SD lnWellness		
Position	0.02	2, 26	0.979	Skill: 1.83 ± 0.25	Mid-Skill: 1.81 ± 0.19	Lineman: 1.81 ± 0.20
Day	<0.001	1,26	0.99	BL: 1.82 ± 0.22	Post: 1.82 ± 0.21	
Position × Time	5.00	2, 26	0.015	SKILL Pre: 1.83 ± 0.26 SKILL Post: 1.83 ± 0.25	MID-SKILL Pre: 1.79 ± 0.19 MID-SKILL Post: 1.83 ± 0.18 [¥]	LINEMAN Pre: 1.83 ± 0.21 LINEMAN Post: 1.80 ± 0.20

* = significantly lower than pre ($p < 0.05$); [¥] = significantly greater than pre ($p < 0.05$).

A significant position \times day interaction was observed for lnWellness (Table 4.1b.). Differences in lnWellness_pre and lnWellness_post20 were not statistically significant for SKILL ($p = 0.922$; ES \pm 90% CL = 0.0 ± 0.42 , *Unclear*) and LINEMEN ($p = 0.074$; ES \pm 90% CL = -0.15 ± 0.47 , *Unclear*). For MID-SKILL lnWellness_pre was significantly lower than lnWellness_post20 ($p < 0.05$; ES \pm 90% CL = 0.22 ± 0.41 , *Small*). Interaction plots are displayed in Figure 4.1b.

Figure 4.1.

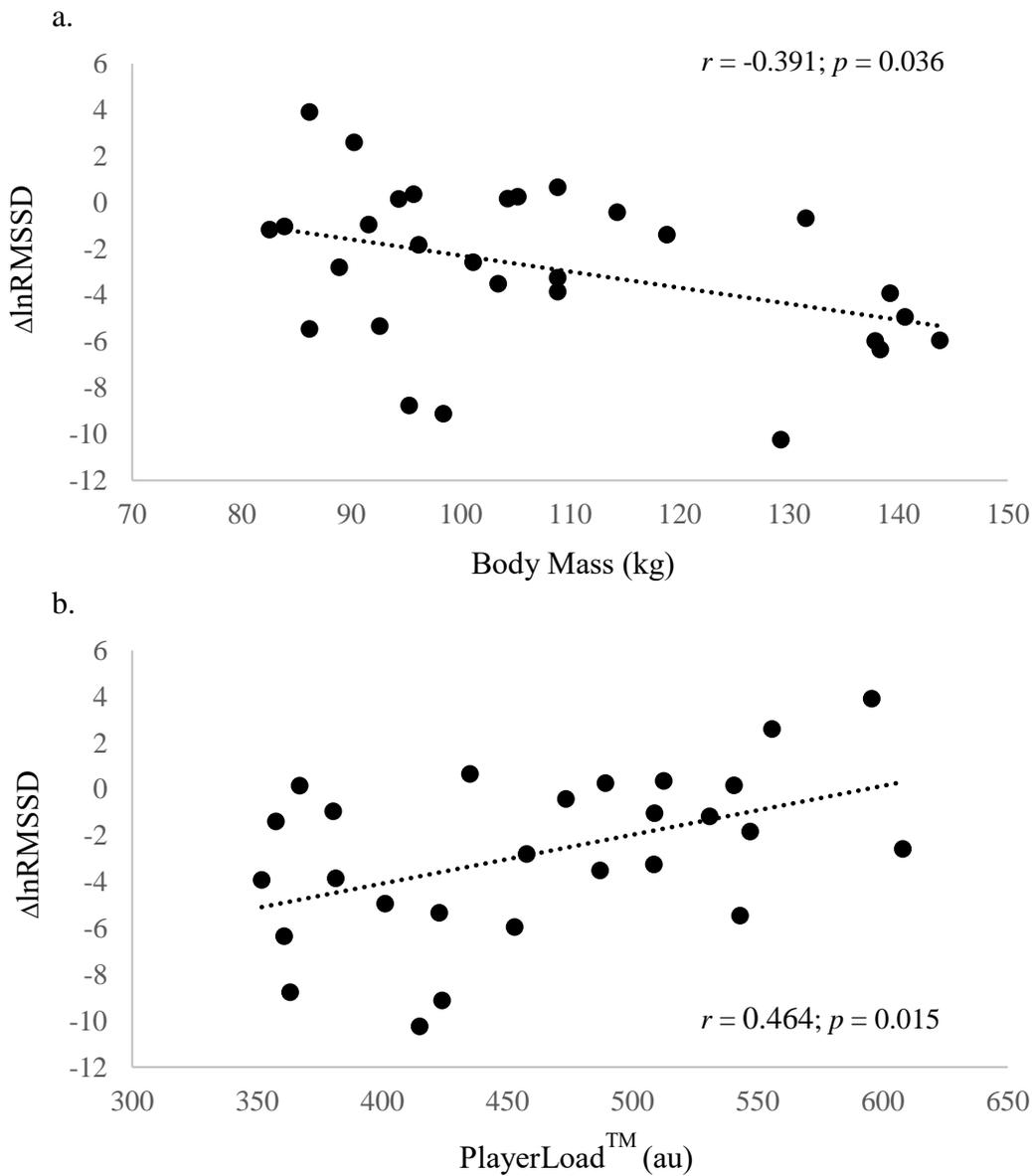


Interaction plots featuring a.) the daily natural logarithm of the root mean square of successive R-R interval differences (lnRMSSD) and b.) lnWellness response to training to training among positional groups.

Dotted lines = SKILL; Dashed lines = MID-SILL and Solid lines = LINEMEN.

A significant positive relationship between $\Delta \ln \text{RMSSD}$ and $\text{PlayerLoad}^{\text{TM}}$ ($n = 27$; $r = 0.464$, $p = 0.015$, *Moderate*) was found indicating that larger reductions in $\ln \text{RMSSD}$ occurred among those with lower $\text{PlayerLoad}^{\text{TM}}$ (Figure 4.2a). A significant negative relationship between $\Delta \ln \text{RMSSD}$ and body mass ($n = 29$; $r = -0.391$, $p = 0.036$, *Moderate*) was found, indicating that larger reductions in $\ln \text{RMSSD}$ occurred among those with greater body mass (Figure 4.2b). $\text{PlayerLoad}^{\text{TM}}$ could not be obtained for 2 LINEMEN and thus were excluded from correlation analysis.

Figure 4.2.



Scatter plots featuring a.) the relationship between the daily change in the natural logarithm of the root mean square of successive R-R interval difference ($\Delta \ln \text{RMSSD}$) and body mass and b.) the relationship between $\Delta \ln \text{RMSSD}$ and PlayerLoadTM.

DISCUSSION

The purpose of this study was to assess the daily cardiac-parasympathetic response to in-season training among elite college football players. An additional aim was to evaluate the relationship between $\Delta \ln \text{RMSSD}$, body mass and training load. The primary finding was that $\ln \text{RMSSD}_{\text{post20}}$ was not meaningfully different from $\ln \text{RMSSD}_{\text{pre}}$ among SKILL, but was substantially reduced for MID-SKILL and LINEMEN. Correlations among $\Delta \ln \text{RMSSD}$, body mass and $\text{PlayerLoad}^{\text{TM}}$ showed that subjects with greater body mass tended to demonstrate greater reductions in $\ln \text{RMSSD}_{\text{post20}}$ while subjects with greater $\text{PlayerLoad}^{\text{TM}}$ tended to demonstrate smaller reductions in $\ln \text{RMSSD}_{\text{post20}}$, though some individual variation was observed (Figure 4.2).

Fitness level is a well-established determinant of the daily $\ln \text{RMSSD}$ response to training with smaller daily reductions occurring among individuals with greater aerobic fitness and vice-versa.⁴³⁻⁴⁶ The position \times time interaction observed in the current study is likely explained, in part, by the varying fitness levels inherent to playing position in American football.¹⁷ No substantial reduction in $\ln \text{RMSSD}_{\text{post20}}$ was observed for SKILL, who are the most aerobically fit positional group in football.^{1,17} The superior fitness levels of SKILL are a result of running demands that greatly exceed MID-SKILL and LINEMEN, demonstrated here via $\text{PlayerLoad}^{\text{TM}}$ and elsewhere via GPS analysis.²⁰ LINEMEN (-6.6%) and to a lesser extent MID-SKILL (-3.9%), demonstrated significant reductions in $\ln \text{RMSSD}_{\text{post20}}$. These responses correspond with their respective fitness levels which are lowest in LINEMEN followed by MID-SKILL when compared to SKILL.^{1,17} From this study, it is unclear how factors apart from fitness level may contribute to the differential $\ln \text{RMSSD}$ response to training among positions. A plausible contributor to incomplete recovery of $\ln \text{RMSSD}_{\text{post20}}$ among LINEMEN and MID-SKILL may be an incomplete

restoration of fluid balance from training-induced dehydration. Larger football players experience greater fluid loss during training which affects plasma volume. Changes in plasma volume levels have previously been shown to impact daily changes in lnRMSSD.¹⁵ Moreover, previous findings of an inverse correlation between body mass and relative fitness⁴⁷ and a positive correlation between body mass and fluid loss during football training^{19,48} may help explain the significant relationship between Δ lnRMSSD and body mass observed in the current study.

In agreement with the current findings, previous studies from non-in-season training periods reported reduced resting lnRMSSDpost20 in collegiate soccer and international rugby players with ES ranging from *Small* to *Moderate*.^{36,43} Daily changes in lnRMSSD among elite futsal players in responses to training varied (ES not reported).⁴⁹ Studies evaluating lnRMSSD responses to in-season training among elite athletes are limited. Thorpe et al.⁵⁰ evaluated daily lnRMSSD following submaximal exercise in an elite soccer team during in-season microcycle's and reported no substantial day-to-day mean differences. This may be due to the high fitness level among elite soccer players⁵¹ and inter-individual variability that exists in cardiac-autonomic responses to training.⁴⁹ This would align with our finding of no significant change in lnRMSSDpost20 among SKILL who may be somewhat comparable to soccer players in terms of aerobic fitness.

Wellness_post20 did not substantially differ from Wellness_pre for SKILL or LINEMEN while a *Small* improvement was observed for MID-SKILL. Previous research evaluating Wellness and lnRMSSD together produced mixed results. For example, reductions in lnRMSSD occurred concurrently with reductions in Wellness in response to intensive training among collegiate soccer players and short-distance swimmers.^{11,52} In contrast, fluctuations in Wellness did not relate with

that of lnRMSSD in elite soccer players.⁵⁰ Taken with the current findings, these discrepancies indicate that Wellness cannot reliably be inferred from lnRMSSD changes and vice-versa.

Collection of lnRMSSD data at the training facility is a limitation of the current study due to the heightened potential for “noise” that may confound resting measures. However, a series of repeated measures (i.e., 3 separate weeks) was included to account for potential noise on a given occasion. Standardizing for time of day and proximity to meals appears to enable meaningful lnRMSSD data collection while enhancing compliance among sports teams.^{36,37,49} However, practitioners are encouraged to maintain communication with athletes regarding recent meals and physical activity to minimize data noise. Direct assessment of fitness was not possible for this study but rather was inferred from training load.^{25,26} Thus, we cannot be certain regarding our interpretation of lnRMSSD changes being explained by fitness level. Finally, data were collected from within the first month of competition representing only one quarter of the regular season. Thus, future research is needed to determine how lnRMSSD responses to training evolve over the course of the season, particularly for MID-SKILL and LINEMEN who do not appear to achieve complete cardiac-autonomic recovery between sessions. Though previous research indicates that chronically suppressed lnRMSSD has been associated with maladaptive training responses,^{10,11} it remains to be determined if incomplete cardiac-parasympathetic recovery has any meaningful performance or health implications for football players. This requires investigation to assess if lnRMSSD changes can be used to support training or recovery interventions.

CONCLUSION

To conclude, the daily lnRMSSD response to intense in-season football training is position dependent and does not necessarily reflect perceptual responses. Subjects with greater body mass

and lower mean training loads tended to show the largest reductions in lnRMSSD while subjects with lower body mass and higher mean training loads tended to show smaller daily changes in lnRMSSD.

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CHAPTER 5

CONCLUSION

American football culture is progressively evolving to a more ‘athlete-centered’ approach to training by showing greater interest in the monitoring and management of recovery status among their players. This is evident in the hiring of sports science practitioners at collegiate and professional levels along with their adoption of player monitoring strategies and technologies for implementation in daily practice. To support this trend, research into the efficacy and practical application of these practices is required to guide coaches and support staff in their efforts to optimize player health and performance.

With the development and validation of mobile applications utilizing ultra-short recording periods,^{14,15} HRV has become a popular tool for monitoring training status in athletes. While HRV has demonstrated promise for reflecting fatigue and adaptation in various athletic populations, its efficacy among American football players has not been previously explored. This dissertation has addressed this gap in the literature by evaluating daily and chronic lnRMSSD responses to training throughout different seasons among elite college football players.

The first study evaluated the effects of a training session on lnRMSSD following ~20 h of recovery during Spring camp. In addition, relationships between chronic training load and chronic lnRMSSD trends were quantified. Following ~20 h of recovery from a football practice, a significant reduction in lnRMSSD for LINEMEN was observed, while lnRMSSD for SKILL and MID-SKILL returned to near or within baseline values. Individual changes in lnRMSSD from

baseline to 20 h post-training were significantly related to body mass. The $\ln\text{RMSSD}_{\text{dev}}$ derived from the entire 4-week Spring camp was significantly related to individual mean training load after adjusting for body mass.

The second study evaluated daily $\ln\text{RMSSD}$ and Wellness responses to a 13-day intensive preseason training camp in hot and humid conditions. After the first few days of training, decrements in $\ln\text{Wellness}$ and increases in $\ln\text{RMSSD}$ that peaked on Day 12 following a day of passive rest among SKILL and LINEMEN were observed. The peak in $\ln\text{RMSSD}$ was associated with the return of $\ln\text{Wellness}$ to Day 1 values. MID-SKILL showed no meaningful changes in $\ln\text{RMSSD}$ while their $\ln\text{Wellness}$ remained chronically suppressed throughout the duration of preseason camp.

The third study evaluated the daily $\ln\text{RMSSD}$ response to the most intense training session of the week across three separate weeks during the first month of the competitive season. Compared to resting values, $\ln\text{RMSSD}$ ~20 h following training was significantly reduced for LINEMEN and MID-SKILL but not for SKILL. The individual changes in $\ln\text{RMSSD}$ from rest to 20 h post training was significantly related to both body mass and training load.

Collectively, the results of this dissertation have shown that $\ln\text{RMSSD}$ responses to training among elite college football players are affected by playing position, body mass, training load and training phase. Football players with greater body mass and lower mean training loads (i.e., LINEMEN) show the largest reductions in $\ln\text{RMSSD}$ while subjects with lower body mass and higher mean training loads tend to show smaller daily changes in $\ln\text{RMSSD}$. While these $\ln\text{RMSSD}$ responses to training were consistent during Spring camp and during the early in-season competitive phase, this trend was obscured during preseason training in hot and humid conditions. Rather than decreasing with accumulated fatigue, $\ln\text{RMSSD}$ tended to increase. Thus, heat

acclimatization responses during preseason camp may prevent typical training-induced reductions in lnRMSSD observed during Spring camp and in-season.

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APPENDIX

November 24, 2015

Office for Research
Institutional Review Board for the
Protection of Human Subjects

THE UNIVERSITY OF
ALABAMA
R E S E A R C H

Andrew A. Flatt
Department of Kinesiology
College of Education
The University of Alabama
Box 870312

Re: IRB # 14-OR-431-ME-R1 "Monitoring Training Effects with
Smartphone-Derived HRV in Collegiate Swimmers"

Dear Mr. Flatt:

The University of Alabama Institutional Review Board has granted approval for your renewal application.

Your renewal application has been given expedited approval according to 45 CFR part 46. You have also been granted the requested waiver of documentation of informed consent for the online survey participants. Approval has been given under expedited review category 7 as outlined below:

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

Your application will expire on November 23, 2016. If your research will continue beyond this date, complete the relevant portions of the IRB Renewal Application. If you wish to modify the application, complete the Modification of an Approved Protocol Form. Changes in this study cannot be initiated without IRB approval, except when necessary to eliminate apparent immediate hazards to participants. When the study closes, complete the appropriate portions of the IRB Study Closure Form.

Please use reproductions of the IRB approved informed consent form to obtain consent from your participants.

Should you need to submit any further correspondence regarding this proposal, please include the above application number.

Good luck with your research.

Sincerely,



358 Rose Administration Building
Box 870127
Tuscaloosa, Alabama 35487-0127
(205) 348-8461
FAX (205) 348-7189
TOLL FREE (877) 820-3066


Carpanato T. Myles, MSM, CIM, CIP
Director of Research Compliance & Research Compliance Officer
Office of Research Compliance

Sports Medicine

THE UNIVERSITY OF
ALABAMA
CRIMSON TIDE

Hi Andrew,

This letter serves as my approval for your study "Monitoring training effects with Smartphone-derived heart rate variability in collegiate athletes, IRB Protocol ID 6253" that involves the University of Alabama Football team.

Thanks,

Jeff Allen
Director of Sports Medicine
Head Football Athletic Trainer
jallen@ia.ua.edu



A handwritten signature in black ink, appearing to be 'JA', written over a horizontal line.



Sports Medicine and Rehab Center
Box 870323
Tuscaloosa, Alabama 35487-0323
(205) 348-3600
FAX (205) 348-9932