COMPREHENSIVE LOAD MONITORING FOR ATHLETE HEALTH IN COLLEGIATE MEN AND WOMEN ATHLETES

by

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LIST OF ABBREVIATIONS AND SYMBOLS

Adenosine Triphosphate .... ATP
Autonomic Nervous System .... ANS
Branch Chain Amino Acids .... BCAA
Cortisol C
Creatine Kinase .... CK
External Load .... EL
Functional Overreaching .... OR
General Adaptation Syndrome .... GAS
Global Navigation Satellite System .... GNSS
Global Positioning Software .... GPS
Heart Rate .... HR
Heart Rate Recovery .... HRR
Heart Rate Variability .... HRV
High Speed Distance .... HSD
Hypothalamic Pituitary Adrenal .... HPA
Interleukin-1-beta IL-1b
Interleukin-6 .... IL-6
Internal Load IL
Internal Movement Analysis .... IMA
National Collegiate Athletic Association .... NCAA
Nonfunctional Overreaching .... NFOR
Overtraining .... OT
Player Load .... PL
Repeated High Intensity Efforts .... RHIE
Tumor Necrosis Factor .... TNF
Testosterone .... T
Testosterone-Cortisol Ratio .... T:C
Total Distance .... TD
Tryptophan .... TRY

ABSTRACT

COMPREHENSIVE LOAD MONITORING FOR ATHLETE HEALTH IN COLLEGIATE MEN AND WOMEN ATHLETES

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An important part of training for sport is to enhance sport performance, achieved through the implementation of progressive overload. However, periods of overload must be balanced with periods of recovery in order for positive adaptations to be engendered and maladaptations (i.e. injury, illness, overtraining) to be prevented. To monitor the balance between overload and recovery, it is suggested for practitioners to assess various measures of training load. Training load encompasses two dimension, both external and internal. External load is the physical work incurred by the athlete during a training session and internal load is the athlete's unique stress response to that physical stimuli. Therefore, it is critical to measure both external and internal load in conjunction with one another. Load monitoring is especially important in collegiate athletes, as they are challenged to balance the demands of their sport with academic and social obligations, placing them in a potential position of high stress. Further, current research has examined

acute responses of load markers, but studies that examine the chronic effect of a competitive season on these markers remains limited. As there is no single identifier of overtraining, many load markers may be assessed, thus making it difficult for practitioners to determine the most practical and effective markers to implement in their programs. Therefore, the purposes of the studies included in this dissertation were to investigate markers of external and internal load, and their relationships, across a competitive season in collegiate athletes. By measuring such markers, it would be possible to 1) determine the effects of a season, as they may help identify the balance between overload and recovery, and also 2) determine the most applicable measures of load to monitor in collegiate athletes' programs. Measures of internal load throughout a competitive season in collegiate women lacrosse athletes (Study 1) and the comprehensive relationship between measures of external and internal load throughout a pre-season in collegiate men soccer athletes (Studies 2 and 3) were examined in order to understand how measures of training load change in response to sport training and to identify relationships among various markers.

CHAPTER ONE: INTRODUCTION

A primary goal of training for sport is to enhance sport performance and reduce injury. Progressive overload, defined as the gradual increase of stress on the body during exercise, has been shown to elicit training gains.[1] However, a balance between periods of overload and recovery must be achieved if adaptations are to be engendered and overtraining (OT) prevented.[1,2] OT status falls on a continuum (Figure 1), consisting of fatigue, functional overreaching (FOR), nonfunctional overreaching (NFOR), and OT.[3] Terminology is defined in Table 1.

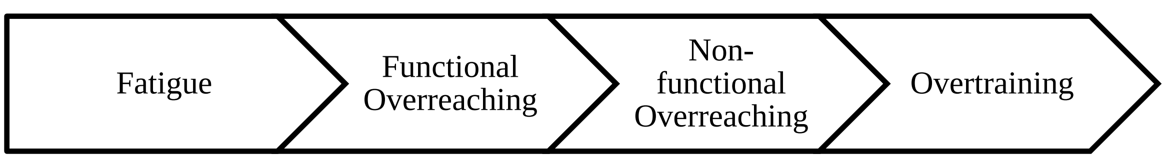

Figure 1. Overtraining continuum[3]

Fatigue develops due to a high volume and/or intensity, with athletes fully recovering and improving performance within 24-48 hours. FOR develops when increased training leads to temporary performance decrements, with improved performance after rest. Athletes may need up to 72 hours,[4] or in some cases, as long as two weeks[5] to recover to achieve positive super-compensation outcomes.[3] NFOR is a condition in which intensified training leads to longer performance decrements (~1-2 months),[3,6] and athletes begin to experience some psychological and neuroendocrinological symptoms, including loss of appetite, increased feelings of tiredness, soreness, and stiffness, higher risk of sickness, sleep disturbances, hormonal imbalance, and lack of enjoyment and confidence.[3,7,8] For performance restoration,[9] athletes may need three weeks to three months of recovery[10] and thus, NFOR is characterized as a negative outcome due to the emergence of symptoms and loss of training time.[3] OT is characterized by the appearance of greater than two months of performance decrements in conjunction with severe psychological (i.e. depression, anger, loss of vigor, lack of concentration, confusion)[3,4,11] endocrinological (i.e. anabolic-catabolic imbalance, inflammation, muscle damage),[12,7,13] and immunological (i.e. increased risk of illness, colds, and infections)[14,15,16] symptoms. It instills a negative adaptation on the athlete due to the severity of the symptoms, time loss from training, and a possible end to their career.[11,17] Therefore, fatigue and FOR are two essential components of any sport periodization and should be planned in order for athletes to improve and achieve super-compensation adaptations; however, NFOR and OT should be avoided as they have shown to be detrimental to athlete health and performance.

Table 1. Overtraining terminology[3]

Term	Definition	Recovery	Outcome
Fatigue	High training leading to temporary performance decrements	24-48 hours	Positive Super-compensation
FOR	Increased training leading to temporary performance decrements. Performance improves after rest.	Days to weeks	Positive Super-compensation
NFOR	Intense training leading to longer performance decrements. Performance recovery after rest accompanied by symptoms.	Weeks to months	Negative
OT	Consistent NFOR but with longer performance decrements and more severe symptoms	Months to years	Negative

FOR: functional overreaching; NFOR: non-functional overreaching OT: overtraining

It has been proposed that OT can be partly explained by the general adaptation syndrome (GAS). In 1983, Seyle proposed that the GAS consists of three phases: alarm, resistance, and exhaustion.[18] During the alarm phase, the body recognizes and responds to the external stressor (i.e. increased training). In the resistance phase, the body undergoes physiological adaptations that allow enhanced homeostasis (i.e. fatigue, FOR). In the exhaustion phase, the body is unable to undergo positive adaptation as it cannot handle the external stimuli (i.e. NFOR, OT).[18] In terms of exercise training, short-term heightened stress placed on the body leads to super-compensation, enhancing performance adaptations.[19] However, if the duration or magnitude of a stressor is placed upon the body with inadequate recovery, performance decrements become present and OT may result (Figure 2).[3,17,20,21,22,23]

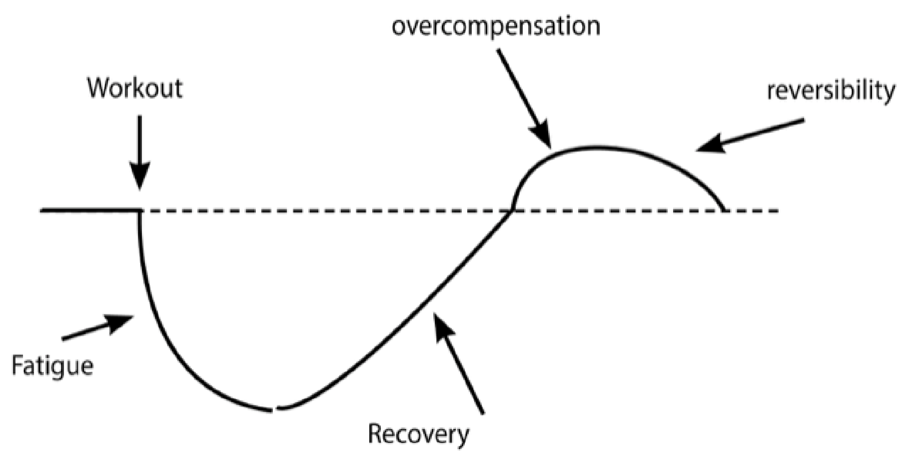

Figure 2. Progressive Overload
After a workout, performance decreases and subsequent rest is needed for overcompensation. If a workout is not conducted during the overcompensation period, performance will not improve and reversal will occur. If a workout is performed during the recovery period, performance will decline and OT may develop.[20]

Because fatigue and FOR can develop into more detrimental conditions (NFOR and OT), it is essential for practitioners to be aware of the multitude of symptoms that may accompany these negative states. There is no single identifiable marker to detect NFOR and OT, thus making diagnosis difficult. Rather, athletes are more likely to experience a combination of symptoms,[24] including physiological and performance imbalances, biochemical alterations, psychological changes, and immunological symptoms (Table 2).

Table 2. Symptoms of NFOR and OT (adapted from Fry[7] and Angeli[25])

Physiological/performance	
Decreased performance	Increased VO_2 at submaximal intensity
Decreased strength and power	Increased resting heart rate (>5 bpm)
Muscle soreness	Decreased heart rate variability
Muscular fatigue	Increased heart rate at submaximal intensity
Loss of appetite	Behavioral changes
Increased injury	
Biochemical	
Increased cortisol	Decreased testosterone-cortisol ratio (>30%)
Decreased testosterone	Increased creatine kinase
Increased interleukin-6	Decreased iron
Psychological	
Depression	Anger
Tiredness	Loss of vigor
Lack of concentration	Restlessness
Immunological	
Increased upper respiratory tract infections	Decreased salivary immunoglobin A
Decreased lymphocytes	Increased severity of minor infections

The emergence of these symptoms can be best understood by examining the proposed OT hypotheses. NFOR and OT are complex conditions and numerous hypotheses have been established in attempt to help explain the development of these symptoms and its relationship to athletic performance. The proposed hypotheses include: 1) glycogen hypothesis, 2) central fatigue hypothesis, 3) glutamine hypothesis, 4) autonomic nervous system hypothesis, 5) hypothalamic hypothesis, and 6) cytokine hypothesis. Understanding the various hypotheses associated with NFOR and OT provides insight in regard to the subsequent symptoms experienced by athletes. In turn, practitioners can monitor their athletes to help ensure improved health and sport performance. Each hypothesis is described below.

Glycogen Hypothesis

Low muscle glycogen can impair performance due to lack of energy.[26,27] Excessive exercise coupled with insufficient carbohydrate intake leads to glycogen depletion and subsequently, a reduction in the rate of adenosine triphosphate (ATP) regeneration. Consequently, the muscle has impaired contractile function, leading to the inability of the muscle to produce force (i.e. fatigue develops).[26] A decrement in sport performance and fatigue are two contributing symptoms of OT, and thus glycogen depletion may be a cause of OT. While this explanation is plausible, research has shown glycogen depleted states are not necessarily associated with performance decrements.[26,27]

Central Fatigue Hypothesis

Several investigators have researched serotonin as a primary cause of OT.[28,29] Exercise increases unbound tryptophan (TRY) and decreases branched-chain amino acids (BCAA) (i.e. leucine, isoleucine, and valine) availability due to its increased utilization for oxidation. The decrease in BCAA availability forces TRY to enter the brain at a high rate, where it is converted to serotonin. Increased brain serotonin is believed to cause mood and behavior changes, including increased depression, reduced sleep, and poor appetite.[28]

These changes are common symptoms associated with OT[29,28] and thus, the reduced BCAA availability may be a contributing factor to the onset of OT. However, few studies have examined serotonin levels in overtrained athletes; therefore, interpretation requires caution.

Glutamine Hypothesis

The glutamine theory states that reduced levels of glutamine following exercise are responsible for reduced immune system functioning.[29,30] Exercise lasting longer than two hours or repeated bouts of high intensity exercise, which is common for many athletes, will decrease blood glutamine production by the overworked muscles.[30] Because glutamine is the primary fuel source utilized by lymphocyte cells, it is suggested that decreased glutamine is associated with increased rate of upper respiratory tract infections and illness.[31] It is unlikely that glutamine is the primary cause of OT, as glutamine levels can be influenced by nutrition, trauma, and infection,[32] but blood levels may be monitored as an indicator of the presence of OT.[31]

Autonomic Nervous System Hypothesis

An imbalance in the autonomic nervous system (ANS) may help explain OT.[29,32] The ANS is divided into the parasympathetic and sympathetic divisions. The parasympathetic division is responsible for the body's "rest and digest" function and restoring the body to a state of calmness (i.e. decreases HR). Conversely, the sympathetic division is responsible for the body's "fight or flight response" and preparing the body for a perceived threat (i.e. increases HR). During exercise, decreased sympathetic activation and increased parasympathetic activation indicate autonomic misbalance. Further, during resting conditions, decreased parasympathetic contribution and increased sympathetic contribution indicate reduced cardiac functioning. Collectively, the altered ANS functioning can lead to performance decrements, fatigue, and depression, all of which are common symptoms of OT.[29,32] Therefore, assessing various HR indices are helpful in understanding ANS balance and provide insight into OT status.

Hypothalamic Hypothesis

Alterations in the hypothalamic-pituitary-adrenal (HPA) and hypothalamic-pituitary-gonadal axes may be responsible for causing OT.[33] Overtrained athletes may have altered testosterone, cortisol, adrenocorticotropic hormone, and other biochemical imbalances, associated with performance decrements and fatigue.[17,29,32,33] Many studies, however, are inconclusive and contraindicative due to the many factors that may influence hormonal levels.[23,32] Therefore, the role of biochemistry markers as a cause of OT cannot be solidified, but may be a useful monitoring tool to determine hormonal imbalances.

Cytokine Hypothesis

Microtrauma to tissues results in the release of cytokines, or inflammatory factors, to initiate healing and strengthening of the muscle.[29,34,35] With continued exercise and minimal rest, this acute inflammation becomes amplified, chronic, and pathologic, and results in systemic inflammation.[32,34,35] The primary cytokines associated with OT include interleukin 1 beta (IL-1b), IL-6, and tumor necrosis factor α (TNF). IL-1b and TNF act on the brain to cause mood disturbances, particularly depressive symptoms, as well as behavioral changes included decreased hunger and sleep.[29] The resulting systemic inflammation appears to be the underpinning theory behind OT as it appears to drive other OT related hypotheses.[29,35]

For example, the glycogen theory as explained previously may result from the released cytokines. Cytokines acting in the hypothalamus may reduce appetite and more severely, induce anorexia, thus leading to decreased glycogen store availability.[29,34,35] Cytokines also interfere with glucose transport into the muscle cells for glycogen synthesis due to downregulation of protein synthesis. Depleted glycogen may evoke feelings of heavy legs, muscular fatigue, and reduced performance.[29,35]

Pro-inflammatory cytokines activate the hypothalamic-pituitary-adrenal axis, causing the release of cortisol. At the same time, these cytokines suppress testosterone, initiating a catabolic state.[29] Therefore, cytokine mediators may be responsible for some hormonal changes within the OT.

As mentioned previously, glutamine is decreased in overtrained athletes, and this may be due to its increased utilization for cytokine-controlled processes.[29,35] Because systemic inflammation causes a catabolic state, IL-6 and TNF stimulate glutamine uptake to aid in protein synthesis. While glutamine has been strongly associated with infection and illness, it is due to the cytokine activation of lymphocytes, that they are able to protect against upper respiratory tract infections.[29,34] While this theory views systemic inflammation as the underlying basis for OT, research is minimal showing elevated cytokine levels in overtrained athletes. More research is needed that explores this relationship.

Training Load Monitoring

The underlying mechanisms of OT provide justification for monitoring these physical, physiological, biochemical, and psychological measures among athletes. Limited research explores a variety of these markers, thus limiting its practicality and applicability for practitioners.

In order to reduce the risk of injury, NFOR, and OT, practitioners can monitor training load. Training load is defined as the cumulative amount of stress placed on an individual from training sessions over a period of time, encompassing both volume and intensity metrics.[8,36] For positive sport adaptations, more does not always equate to better. Increased training requires adequate recovery to attain enhanced performance while reducing the risk of OT.[1,8] Therefore, the quantification of training load is an important aspect of athlete monitoring to ensure sufficient overload-recovery balance.

Training load encompasses both external and internal dimensions (Table 3). External load (EL) is an objective measure of the physical work incurred by athletes during training or competition,[8,37] independent of their internal characteristics.[8] Common markers of EL include Global Navigation Satellite System (GNSS)/Global Positioning Software (GPS) measures to examine both volumes (i.e. total distance (TD), total duration, and player load (PL)) and intensities (i.e. high speed distance (HSD), internal movement analysis (IMA), repeated high intensity efforts (RHIE), sprint efforts, and maximal velocities) achieved.[8,37] These measures provide information in regard to distances traveled, sprint efforts, acceleration bouts, force development, peak power, and general movement patterns.

Any EL measure that contributes to the development of fatigue will result in unique individual stress responses, referred to as internal stress. Because research focuses on stress in response to EL measures, research commonly uses the term internal load (IL) to describe the exposure of stress on the athlete.[38] IL is defined as the relative physiological (i.e. resting[39,40] and submaximal[8,41] HR, heart rate variability (HRV),[39,32,42] and heart rate recovery (HRR)[43,44]), biochemical (i.e. anabolic-catabolic balance: testosterone (T), cortisol (C), and their ratio (T:C); inflammation: interleukin-6 (IL-6); muscle damage: creatine kinase (CK), metabolic (i.e. blood lactate), and psychological (i.e. self-reported measures including fatigue, soreness, stress, energy, mood, sleep, and perceived exertion) stressors imposed upon the athlete.[8,37] These measures provide quantification of an athlete's stress response to a given training stimulus and may be subsequently used to monitor recovery levels.[8]

Table 3. External vs internal training load measures

EL	IL
Volume • Total distance • Player load • Total duration	**Physiological** • Resting heart rate • Heart rate variability • Exercise heart rate • Heart rate recovery
Intensity • High speed distance • High internal movement analysis • Repeated high intensity efforts • Player load/minute • Velocity	**Biochemical** • Testosterone • Cortisol • Testosterone-cortisol ratio • Creatine kinase • Interleukin-6 • C-reactive protein • Immunoglobin-A
	Subjective self-assessments • Wellness • Mood • Sleep
	Metabolic • Lactate

*List is not exhaustive of all external and internal load measures. The table includes the most popular measures examined in athletes in the current body of literature.

Load monitoring is an important tool to determine whether or not athletes are adapting to the training plan and to minimize risk of injury, illness, and OT.[8] Currently, research examines EL in respect to differentiated load by sport-position, mean distances covered, load by halves, and load by starting status. All provide useful information that assists practitioners in creating individualized programs for their athletes to ensure adequate recovery is balanced with the exposed overload. However, the problem with sole examination of EL is that it provides no information in regard to athletes' internal stress response. For example, two athletes may complete the same physical demand in training, but it is incorrect to assume both athletes internally adapt in the same manner.

On the other hand, IL research has examined HR, HRV, HRR, T, C, T:C, mood, wellness, and sleep to determine how athletes adapt to their given training program. However, sole examination of IL provides no information in regard to the situation that caused this stress response. For example, without EL data reported, practitioners cannot determine whether the high stress resulted from the training load, from a stressful week at school, or a stressful social or family situation. Because the body cannot distinguish one form of stress from another, EL is needed to verify the effect of load on the athletes' stress response.

The key to successful and effective load monitoring is to measure EL and IL markers in conjunction with one another, as this provides insight into the physical work performed by the athletes in addition to their stress in response to the stimulus. The benefits of scientific monitoring of athletes include documenting changes in performance, increasing the understanding of training responses, revealing fatigue and accompanying needs for recovery, informing the planning and modification of training programs, and ensuring appropriate load to minimize the risk of OT. However, because no single marker exists that predicts maladaptation, a wide variety of measures are available to monitor load and the subsequent stress imposed upon the athlete.

Currently, there are four main gaps in the training load literature. First, women athletes are understudied, with no research examining load monitoring in female lacrosse athletes. Second, studies involving collegiate athletes are limited, in part due to the high expense of load monitoring research methodology and technology involved. Third, research lacks a comprehensive analysis of the relationships among various load markers. Because there are many identifiable markers of NFOR and OT, more research is needed to determine how they relate to one another in order to provide practitioners with the most optimal recommendations for monitoring their athletes. Last, less studied in the literature includes lack of routine, longitudinal load monitoring assessments, particularly during critical periods (i.e. pre-season, competitive season) in a training cycle for collegiate-level athletes. Here, athletes are exposed to cumulative and chronic stress, which may affect their health and performance for the remainder of their season.

The incidence of OT varies widely across sports, with reports of approximately 67% of elite distance runners and cyclists, and 20-50% of swimmers, basketball, soccer, and individual and team sport players being affected.[45] While load monitoring has gained popularity in professional men's sports, much less is known about collegiate field sport athletes, particularly women athletes. These players may be at a higher risk for OT due to the physical and non-physical life stressors they are exposed to as collegiate students, including academics, social activities, relationships, and poor dietary and sleep behaviors. With over 150,000 National Collegiate Athletic Association (NCAA) Division I collegiate athletes on scholarship,[46] they are expected to perform at the highest level of competition; if they become injured, ill, or overtrained, these athletes no longer can perform at the required level and are at risk of losing their funding and position on the team. Therefore, it is of upmost importance that these athletes remain healthy and continue to improve their performance throughout their athletic career.

In addition, there is no single identifier to diagnose OT, making it difficult to conclude the training status of athletes. Current studies lack comprehensive analysis of the variety of markers available, which would serve useful for practitioners who are deciding what load measures to utilize for their athletes. Limited research exists, particularly at the collegiate level, and these relationships remain inconclusive and in contrast. Therefore, the central aim of this dissertation is to comprehensively examine the relationship among various dimensions of training load (i.e. external and internal load measures) in NCAA Division I athletes from the sports of lacrosse and soccer. Secondly, it is to assess longitudinal changes in training load markers as a result of a competitive period (i.e. in-season and pre-season phases).

Specific Aim of Study 1: To 1) provide descriptive data in resting hormonal (T, C, T:C) and physiological (resting HRV) responses across a competitive season in NCAA Division I women lacrosse athletes, and 2) determine the relationship between internal load measures of hormonal (T, C, T:C), physiological (HRV), and self-assessments of fatigue and recovery.

Hypothesis: It is hypothesized that HRV and hormonal balance (T:C) will decline throughout the season, and 2) physiological (HRV), hormonal (T, C, T:C), and self-assessment measures (fatigue, recovery) will all be related.

Specific Aim of Study 2: To describe the relationship and predictive value between objective (EL – TD, PL, HSD, IMA, RHIE) and self-assessment wellness markers (IL – fatigue, soreness, stress, energy, sleep, mood) of training load throughout a pre-season window in NCAA Division I men soccer athletes.

Hypothesis: It is hypothesized that volume (TD, PL) and intensity (HSD, IMA, RHIE) will be positively related to fatigue, soreness, stress, and negative mood, and inversely related to energy and sleep.

Specific Aim of Study 3: To describe the comprehensive relationship and predictive value between objective (EL – TD, PL, HSD, IMA, RHIE) and 1) physiological measures (HRV, exercise HR), 2) hormonal measures (T, C, T:C), and 3) subjective measures of training load (fatigue, soreness, and stress, energy, mood and sleep**)** throughout a pre-season window in NCAA Division I men soccer athletes

Hypothesis: It is hypothesized that volume (TD, PL) and intensity (HSD, IMA, RHIE) will be negatively related to resting HRV, T:C, energy, mood, sleep) and positively related to exercise HR, C, fatigue, soreness, and stress.

CHAPTER TWO: LITERATURE REVIEW

Methods of Load Monitoring

External Load

EL is the physical work incurred by the athlete during a given training session. Sports scientists and coaches typically inquire about two outcomes following each training session: 1) how much work did their athletes complete and 2) how hard did their athletes push themselves to complete that work. To answer these questions, measures of training volume and training intensity can be analyzed via GNSS technology, a device that is composed of an accelerometer (acceleration), gyroscope (angular velocity), magnetometer (orientation in relation to the Earth's magnetic field), and GPS (position). These devices have made it possible to quantify the kinetic demand in training and competition by recording localization and covered distances and speed, through latitude and longitude coordinates.[47,48] The use of these devices has made it possible to understand the specific load demands across a variety of sports teams.[49]

To assess volume accruement during training through GNSS/GPS technology, common measures include total duration (i.e. how long the session lasted), total distance (TD) (i.e. how much distance was covered, at any intensity, during the session), and total player load (PL) (i.e. any, and all, movement in the x-, y-, and z-planes). When duration, distance, and/or player load is high, there is increased movement on the field and overall volume is considered high for that training session.

To assess training intensity, measures commonly include high speed distance (HSD) (i.e. total distance covered at > 13.5 mph), maximum velocity (i.e. highest velocity achieved), acceleration efforts (IMA) (i.e. number of efforts an athlete reached an acceleration > 3.5 m/s^2), repeated high intensity efforts (RHIE) (i.e. the number of times an athlete completed consecutive sprints within 21 seconds of one another), and player load per minute (PL/min) (i.e. total movement performed in one minute). Higher values would suggest a higher intensity performance during training because the movements performed were quick and explosive. Collectively, these measures provide information in regard to the physical stimuli that was imposed on the athlete during their training.

External Load and Sports Performance

Results from competitive sports games have shown differentiated load by sport-position[50,51] mean distances covered,[52,53,54] as well as performance intensity measures. In elite men soccer athletes, players covered on average 10,776 ± 107 m, with 668 ± 28 m and 143 ± 10 m being HSD (19.8 to 25.2 km·h⁻1) and sprinting (≥25.2 $km \cdot h^{-1}$), respectively.[54] Central midfielders covered higher TD (11,570 ± 469 m) than central defenders (9,830 ± 428 m), wide defenders (10,747 ± 420 m), wide attackers (10,918 ± 353 m), and strikers (10,320 ± 420 m).[54] This may be due to the positional demands of central midfielders, requiring both attacking and defensive style of play and thus, a subsequent need to cover more distance.[95] Wide attackers and wide defenders reached higher maximal speeds (8.6 ± 0.4m/s and 8.4 ± 0.4 m/s, respectively) compared to central defenders (7.4 ± 0.3 m/s), central midfielders (7.5 ± 0.3 m/s), and strikers (7.6 ± 0.5).[54] All positions covered more HSD compared to central defenders.[54] In general, wide positions had greater sprinting, HSD, IMA, and decelerations when compared to the central field players, indicating higher intensity exposures.

Reports of elite women soccer players indicate these athletes cover less TD (9,631 ± 175 m) compared to their elite men counterparts,[54] with 2,407 ± 125 m from HSD (12 to 19 km·h⁻1) and 338 ± 30 from sprinting (>19 km·h⁻1).[55] Defenders covered less TD (8759 ± 284 m) and HSD (1744 ± 138 m) than midfielders (10150 ± 22 m; 2797 ± 174 m, respectively), and less sprint distance (188 ± 31 m) compared to midfielders (392 ± 46 m) and attackers (388 ± 56 m).[55] Further, midfielders covered the greatest TD, and achieved the highest low-intensity activity, whereas forwards covered the greatest distance at high-intensity.[55]

Also, heavily researched are elite rugby men players, where athletes covered on average 6,953 m during a game. Of this, 37% (2800 m) was spent walking, 27% (1900 m) jogging, 10% (700 m) cruising, 14% (990 m) striding, 5% high intensity running (320 m), and 6% (420 m) sprinting.[52] Positional data indicated that backs cover more TD (6917 ± 1130 vs. 4181 ± 1829 m), more sprint distance (316 ± 117 m vs. 119 ± 86 m), higher max sprint distance (58.0 ± 24.0 m vs. 39.0 ± 20.0 m), and higher peak speed (30.1 ± 2.9 m/s vs. 25.2 ± 1.2 m/s) compared to forwards.[50,52]

Studies have also differentiated workload based upon starting status in elite men soccer players.[56] Compared to starters (>65 minutes played), non-starters (substituted into game) covered greater match distance within the following velocity categories:

>3.3≤4.2m/s, >4.2≤5 m/s, and >5≤6.9 m/s. In contrast, similar match average acceleration and deceleration values were identified for starters and non-starters. However, Anderson et al.[57] showed that TD did not differ between starters (started ≥60% of games), fringe players (started 30–60% of games) and non-starters (started <30% of games). Starters did complete more distance running at 14.4–19.8 km/h (91.8 ± 16.3 vs 58.0 ± 3.9 km; effect size (ES)=2.5, p<0.05), HSD at 19.9–25.1 km/h (35.0 ± 8.2 vs 18.6 ± 4.3 km; ES=2.3, p<0.05), and sprinting at >25.2 km/h (11.2 ± 4.2 vs 2.9 ± 1.2 km; ES=2.3, p<0.05) than non-starters. In addition, starters completed more sprinting than fringe players, who accumulated 4.5 ± 1.8 km (EF=2.0, p<0.01).[57] These demonstrate that substantial performance differences in elite soccer matches between starters and non-starters exist and thus, stress responses may differ and subsequent recovery strategies may be dependent upon exposure.

Practitioners may also use EL to understand performance differences between separate halves. It is shown that volume and intensity decrease from the 1st to the 2nd half in elite soccer (men and women), Australian football, and rugby athletes.[58,59,60,61] Soccer match comparisons reveal that PL, TD, low intensity activity, and high-intensity activity decrease in the second half with small to moderate effect sizes.[60] Specifically, TD covered in the first half (5,173 m) was higher than distance covered in the second half (4,808 m).[58] In fact, minute-by-minute analysis revealed that after just eight minutes of the second half, player performance had decreased, a reduction that was maintained throughout the second half.[58] A substantial decrease in the distance covered at >14.0 km/h and >18.0 km/h, the number of accelerations of >2.78 m/s and >4.0 m/s, RHIEs interspersed with ≤60 s rest, and repeated-acceleration sequences interspersed with ≤30 s or ≤60 s rest was observed in the 2nd half compared with the 1st half.[61]

Further, movement demands declined from 1st to 2nd half in sub-elite (n=105) and elite (n=210) men Australian football athletes.[59] As seen in sub-elite levels, TD (6506 ± 964 m vs 5998 ± 1167 m, $p<0.01$), distance/minute (127 ± 17 m vs 114 ± 16 m, $p<0.05$), high intensity efforts (>15 ml/hr) (138 ± 35 vs 120 ± 34, $p<0.01$), and sprint efforts (>20 km/hr) (42 ± 14 vs 36 ± 15, $p<0.01$) were significantly higher in the 1st half compared to the 2nd half.[59] Similar observations were seen for elite level footballers for distance/minute (131 ± 13 m vs 125 ± 14 m, $p<0.01$), high intensity efforts (141 ± 31 vs 130 ± 33, $p<0.01$), and sprint efforts (39 ± 13 vs 35 ± 12, $p<0.01$).[59] In addition, men elite rugby athletes showed reductions from 1st to 2nd half in distances covered >14 km/hr (41.7 ± 12.6 m/min vs 36.4 ± 7.6 m/min, 12.7% reduction, effect size: small) and >18 km/hr (21.9 ± 9.9 m/min vs 16.3 ± 5.9 m/min, 25.6% reduction, effect size: small), as well as the number of accelerations at >2.78 m/s^2 (7.8 ± 2.0 m/s^2 vs 5.3 ± 3.0 m/s^2, 32.1% reduction, effect size: large) and >4.0 m/s^2 (0.5 ± 0.6 m/s^2 vs 0.2 ± 0.4 m/s^2, 60% reduction, effect size: small), and the number of sprints efforts (5.2 ± 2.3 vs 3.8 ± 1.8, 26.9% reduction, effect size: moderate).[61] Identification of these differences enables coaches and analysts to potentially prescribe optimal training loads to improve player performance throughout the entire competition. However, additional research is needed to examine these differences in collegiate level athletes.

External Load and Injury Prevention

Acute-to-Chronic Workload Ratio

Originally proposed by Banister in 1975, the fitness fatigue model states that the training stress placed on an athlete results in two conflicting responses: fitness and fatigue.[62] Fitness results in positive physiological responses and thus, improved performance, whereas fatigue results in negative physiological responses and diminished performance, potentially increasing subsequent risk of injury. Based on this paradigm, the acute-to-chronic workload ratio (ACWR) was developed to compare the acute workload (i.e. 1-week workload) and chronic workload (i.e. 4-week rolling average acute workload). The difference between the positive physiological response and the negative physiological response provides either a low (chronic workload is greater than the acute workload) or high (acute workload is greater than the chronic workload) ACWR. A comparison of the acute load to the chronic load as a ratio is therefore a dynamic representation of a player's preparedness, and ultimately considers the training load the athlete has performed relative to the training load the athlete has prepared for.[63]

Because elite level athletes are often required to play consecutive matches within 72 hours of one another, they are inherently exposed to high loads and potentially less recovery time.[63,64] Consequently, the ACWR has been used by practitioners to determine the optimal workload to improve fitness while simultaneously reducing injury risk among their athletes.

For example, in elite men rugby players, a very-high ACWR of ≥2.11 was associated with an injury risk that was 1) 6.9x greater than an ACWR <0.30, 2), 3.4x greater than an ACWR 0.31-0.66, 3), 2.3x greater than an ACWR 1.03-1.38, and 4) 2x greater than an ACWR 1.75–2.10. ACWRs >1.6 coupled with limited recovery were 3.4-5.8x more likely to sustain a match injury than players with lower ratios (90% CI 1.17 to 19.2); likelihood range 96–99%, very likely).[63] Further, these athletes were more resistant to injury with ACWRs between 0.85-1.35, and less resistant to injury when drastic spikes were observed in acute workloads.[63]

Elite Gaelic football players were also at a heightened risk of injury when periods of low training load were followed by drastic spikes in training load (ACWR >1.5).[65] Players with 1 year of experience had a significantly higher risk of injury (odds ratio = 2.22) and players with 2–3 years (odd ratio = 0.20) and 4–6 years (odds ratio = 0.24) of experience had a lower risk of injury, most likely due to exposure of loads.[65] Further, players with poorer aerobic fitness (estimated from a 1-km time trial) had a higher injury risk than those with higher aerobic fitness (odds ratio = 1.50–2.50). Overall, an ACWR of ≥2.0 demonstrated the greatest risk of injury.[65] Similarly, men English Premier soccer players were at highest risk of injury when ACWR spikes approached or exceeded a ratio of 2.0.[66]

In professional men soccer players, risk of injury was increased when TD ACWR TD was high (>1.76) (relative risk=4.98, 95% CI 1.31 to 19.02, p=0.019). Injury risk was also elevated for HSD ACWR between 1.41-1.96 (relative risk=2.55, 95% CI 1.15 to 5.68, p=0.022). Last, risk of injury was increased when acceleration and deceleration ACWR was >1.77 (relative risk=4.98, 95% CI 1.30 to 18.99, p=0.019), >2.0 (relative risk=6.7), respectively.[66] Thus, utilizing various EL measures in a ratio may provide valuable information in regard to injury development.

Despite some original research demonstrating a relationship between ACWR and injury, this measure is considered controversial and thus, its interpretation in practical settings warrant caution. First, a majority of the published literature that exists in regard to the ACWR are opinion pieces rather than experimental studies. This makes it difficult to interpret the practical use of the ACWR in relation to injury status for athletes.

Second, the ACWR may be calculated using a chronic workload of either three or four weeks, and may be calculated from a variety of measures (i.e. TD, PL, HSD, accelerations, decelerations, sRPE, etc.). For example, Colby et al. found a chronic three-week load of TD (odds ratio: 5.489, p=0.008) and chronic four-week load of velocity change (odds ratio: 2.244, p=0.035) were associated with greater injury risk in elite Australian footballers.[67] Further, three-week workloads of TD (p=0.05), HSD (p=0.04), and power (p=0.05), and four-week workloads of HSD (p=0.02) and power (p=0.05) showed strongest relationships to injury risk in professional rugby players.[68] For these reasons, this poses questions for the practitioner, including what number of weeks to include as the chronic measure, and which external load marker(s) to follow since not all measures yield similar results.

Last, there is no universal, ideal value to achieve using the ACWR. It has been proposed that a ratio of ~1.5, or 0.8-1.3 is the optimal “sweet spot” for lowest injury risk.[69,70] However, this recommendation was solely based on two original research studies in elite men cricket fast bowlers[71] and rugby players,[63] and data was manipulated in an inappropriate and unreliable calculation.[72]

Overall, the ACWR may provide useful information for practitioners, but its predictability of injury should be interpreted with caution. Values may be combined with other measures of load for a more comprehensive understanding of training status. Further, practitioners must consider the sport-specific schedule of competition and training when choosing acute and chronic time windows.[73] Much of the primary investigations into the ACWR are measured in elite athletes and little is known about the use of ACWR in collegiate men and women athletes.

Volume and Intensity Measures

Through analyzing volume and intensity metrics, coaches can improve their sport programming to simulate real-life game play and reduce risk of injury.[74] Assessment of EL has shown that athletes who engaged in ‘moderate’ high speed running and sprinting at practice, compared to ‘low’ high speed running and sprinting, were at a reduced injury risk throughout the season (odds ratio: 0.12, p=0.001). Authors speculate this is because the athletes had more exposure outside of games to high speed running and sprinting, which minimized large weekly changes in running speeds, allowing their bodies to adapt more efficiently to the high loads.[74] However, sprinting should not exceed 9 m/s per session, as this speed was associated with a 2.7x higher risk of injury.[75] In addition, higher volume (i.e. distances covered in mild and moderate speeds) allowed players to tolerate high distances, with these exposures approaching a significant protective effect on injury risk (odds ratio = 0.23, p = 0.055).[74]

Further, players performed a significantly higher number of meters per minute preceding an injury compared with their seasonal averages (+9.6%, $p<0.01$), indicating an increase in training intensity may leave athletes unable to recovery adequately and place them at a higher risk of injury. From an injury prevention perspective, these findings provide empirical support for restricting the amount of sprinting performed in preparation for elite team sport competition. However, coaches should also consider the consequences of reducing training loads on playing performance. Therefore, there must be a balance between high and low intensity exposures, as periods of undertraining could potentially cause players to be underprepared for the intense demands of competitive matches.[75,76] It is important to note that all loads should be individualized per player and thus, load thresholds might be determined for individual athletes. Loads above their threshold may increase risk substantially.[67]

EL data provides useful information in regard to athlete work, whether it be position specific, match demands, half comparisons, or injury-related. However, it provides no information on the internal stress response to the load.

Internal Load

IL is the athlete's stress response to the given physical work incurred during training. There are four divisions within IL that provide insight to the stress response, including physiological, biochemical, metabolic, and subjective measures.

Physiological Mechanisms

Changes in the autonomic nervous system (ANS) are proposed to be sufficient at measuring training status. Therefore, examining ANS response to training load throughout a competitive period provides insight in regard to the body's ability to recover or adapt to an external stimulus. The ANS controls cardiovascular function through the parasympathetic and sympathetic nervous systems. The parasympathetic division is responsible for calming the body back to a restful, homeostatic state (i.e. decreasing HR), while the sympathetic division prepares the body for threat (i.e. increasing HR).[77] The balance between parasympathetic and sympathetic contribution is altered following exercise training and thus, monitoring HR may indicate an athlete's responsiveness to and readiness for training. This has become a popular method for measuring training load due to its non-invasive, quick, and cost-effective methodology.[54,55] Two popular measures of autonomic HR include heart rate variability (HRV) and post-exercise heart rate recovery (HRR). Other markers include resting HR, sleeping HR, exercise HR (measured by training impulse (TRIMP)).

HRV is the assessment of variation in time between consecutive R-R intervals, or heartbeats.[78] The time between R-R intervals fluctuates as a result of the interaction between ventilation, blood pressure, and cardiac output in order to maintain blood pressure homeostasis. The oscillations of a healthy heart are complex and non-linear, and beat-to-beat fluctuations can be best described as mathematical chaos.[79] A high HRV demonstrates increased parasympathetic contribution and decreased sympathetic contribution, suggesting cardiac function is efficient and athletes are positively adapting to their training stimulus. On the other hand, a depressed HRV signifies decreased parasympathetic contribution and increased sympathetic contribution, suggesting recovery is poor and subsequent rest may be needed prior to returning to training.

Most commonly, HRV is presented in either a frequency-domain or time-domain. Frequency-domain measurements estimate the distribution of absolute or relative power into four frequency bands: ultra-low-frequency (ULF), very-low-frequency (VLF), low-frequency (LF), and high-frequency (HF).[80] The LF:HF is widely utilized as a marker of sympathetic-to-parasympathetic balance, as it reflects a shift towards sympathetic control and reduced parasympathetic contribution,[81,82] which is commonly seen during NFOR and OT. LF:HF is often studied in response to acute exercise to track the transition from sympathetic dominance to parasympathetic rebound during recovery.[83] However, frequency-domain measurements are restricted to a clinical laboratory setting due to sophisticated software, expensive heart rate recording equipment, and the extensive technical knowledge required for interpretation. Further, a 5-minute recording minimum is recommended for frequency-domain measurements, which may not be suitable for time-restricted athletes in a sport setting.[84]

As an alternative, time-domain measurements are commonly analyzed, which quantify the amount of variability in between successive heartbeats.[80] These values may be expressed in original units or as the natural logarithm (ln) in order to achieve a more normal distribution. The root mean square of successive normal-to-normal interval differences (RMSSD) has a number of advantages for HRV monitoring among athletes. For example, shorter and more convenient 1-minute measurements can be used to obtain accurate assessments of cardiac autonomic changes in men and women collegiate athletes, and it is has shown to be less influenced by breathing rate.[85,86,87] RMSSD from the 1-min segments provided very large to nearly perfect correlations (r values ranged from 0.71-

0.97, $p < 0.001$ for all) to LF, HF, and LF:HF, suggesting that ultra-shortened time-domain markers may be useful replacements of the frequency-domain parameters for tracking changes in parasympathetic-sympathetic activity in athletes.

The variety of methods used for assessing HRV, has resulted in inconsistent results from high-level athletes, and thus the validity of such measures come into question.[82,88,39,40,89,90] It is advised, therefore, that HRV measurements be averaged over 7 days to detect changes related to training load adaptations, as single day values may be misleading.[42,91] The coefficiant of variation (CV) of lnRMSSD (lnRMSSDcv)) may be used as it reflects the daily fluctuation in lnRMSSD across a training week and is believed to reflect the stress and recovery process in response to training.[92,93]

It has been proposed that valid HRV measurements should be taken immediately upon waking in order to obtain a true resting condition. However, it has been shown that measures of lnRMSSD taken immediately upon waking and a few hours following waking prior to practice were moderately correlated with 30-minute distance ($r=0.40$, $r=0.41$, respectively) in collegiate rowers.[94] However, 2000 m time was only related to lnRMSSD upon waking ($r=0.37$, $p<0.05$). Therefore, while both may be related to performance, waking lnRMSSD might be slightly more applicable to observe these positive relationships.

Heart rate recovery (HRR) is the assessment of the rate at which HR decreases following the cessation of exercise,[95] and reflects the interaction between parasympathetic re-activation and sympathetic withdrawal.[96] A faster HRR is a reflection of parasympathetic dominance, whereas a slower HRR is due sympathetic dominance. A slow

HRR reflects inability of the heart to efficiently recover, thus signifying maladaptation to the current training load.[38,43,97] HRR can be collected over varying time frames, ranging from 30 seconds to 2 minutes; however, 60 seconds post-exercise is most commonly used and yields the highest level of agreeability.[43]

HRR has been long associated with endurance training and aerobic fitness in trained individuals and athletes.[97,98,99,100] HRR has shown to be quicker in trained individuals compared to their untrained counterparts[100,101] and has decreased in response to aerobic and high intensity training programs,[102] signifying cardiovascular adaptation. Consequently, HRR may be a more sensitive measure of autonomic training adaptations in athletes compared to HRV, as it has shown to be highly related to peak power output and 40km time trials in cyclists,[97,103] and physical activity volume ($r = 0.67$, $P = 0.003$), and VO_{2max} ($r=0.51$, $p= 0.039$) in well-trained endurance athletes.[104]

Despite the role of both HRR and HRV in assessing autonomic function, they appear to be unrelated to one another ($p>0.05$).[105,106,107] Percent decrease of HR during the first and second minutes of recovery was not related to HRV parameters assessed during supine and standing positions.[105,107] However, those with a higher resting HRV had lower HRs at maximal exhaustion, despite no difference in HRR.[107] Therefore, it is suggested that the two measures might bring separate but complementary information pertaining to cardiac parasympathetic function. HRR may be more strongly related to weekly training load but HRV indexes may be more associated with cardiorespiratory fitness.[108]

Sleeping HR is another index that has shown to be a more sensitive and reliable measure of HR as it is less likely affected by extraneous variables.[109] Nocturnal HRV was lower after high volume (>90 minutes) training sessions (RMSSD: 56 ± 25 ms) compared to rest days (75 ± 33 ms, $p < 0.01$). Interestingly, intensity (easy, moderate, hard) had no effect on nocturnal HRV (72 ± 29 ms, 71 ± 38 ms, 66 ± 37 ms, respectively).[110,111] However, sleeping HR is not routinely assessed in athletes due to lack of equipment and resources.

Last, training impulse (TRIMP) has gained popularity as an internal measure of volume and intensity during sport training. There are several TRIMP equations, but the two most common include Bannister's TRIMP (Load = [duration (min)](average HR during exercise – resting HR)/(max HR – resting HR)x0.64$e^{1.92x}$), where e=2.712 and x=(average HR during exercise-resting HR)/(max HR – resting HR), and Edward's TRIMP (Load = (duration in zone 1)+(duration in zone 2)+(duration in zone 3)+(duration in zone 4)+(duration in zone 5)).[112,113] Therefore, minutes accumulated at each different HR zones can also be used to identify the levels of stress and to quantify the IL in training sessions. As exercise intensity increases, HRs will increase, thus increasing TRIMP values.

Physiological Measures and Performance

HR indices have shown promising relationships with athlete physical performance. There was a large correlation between ΔlnRMSSD and ΔYo-YoIR2 (r=0.74, p=0.006) in women collegiate soccer athletes, indicating that athletes who showed a decrease in lnRMSSDcv from weeks 1-3 experienced a greater improvement in aerobic fitness. Changes in total high intensity running (>14.4 km h^{-1}) showed very large relationships with weekly changes in lnRMSSD,[114] and exercise HR (r=0.8) in elite men soccer and football athletes.[115,116] However, sample sizes were small (n=10-18) and limited research exists to confirm this relationship. Further, these measures of HR were only measured across a 2-3 week period, and thus more routine longitudinal data is needed to verify this relationship in response to a competitive season.

In collegiate rowers, 60-second HRR was faster during pre-season compared to post-season and was inversely related to time to exhaustion. However, HRR was not related to aerobic capacity ($p=0.279$),[117,118] indicating that it may be a more promising measure of training status, rather than fitness level.[117] Resting RMSSD, however, was related the time to perform a 10km run ($n=10$, $r=-0.71$, $p=0.012$) perhaps suggesting that enhanced parasympathetic function at rest may be a condition to a better performance for endurance athletes.[118] However, Boullosa et al. observed an unclear relationship between nocturnal HRV and performance on the Yo-Yo field test in elite men soccer players. Athletes were assessed weekly over 8 weeks, and no relationship was observed at any week, except week 8 ($r=0.898$, $p=.006$).[119] These findings may be attributed to the varying methodology associated with HRV and warrant further investigation.

A 2016 meta-analysis investigated the relationship among exercise stimulus, HRV, and HRR. Studies showing increases in performance showed small increases in resting RMSSD (standardized mean difference (SMD)=0.58, $p<0.001$) and moderate increases in post-exercise RMSSD (SMD=0.60, $p<0.001$) and HRR (SMD=0.63, $p=0.002$).[119,120,121,122,93,44] However, studies showing reduced performance also reported small increases in resting RMSSD (SMD=0.26, $p<0.01$) and HRR (SMD=0.46, $p<0.001$) and moderate increases in post-exercise RMSSD (SMD=0.64, $p=0.04$).[123] Therefore, while favorable changes in RMSSD and HRR have been associated with improved performance, increases have also been reported with reduced performance and overreaching,[124,125,126] and thus, additional measures of training stress are needed in conjunction with HR.[123]

Biochemical Mechanisms

Assessing biochemical status provides information in regard to anabolic-catabolic balance, muscle damage, and immune system functioning.

<u>Testosterone</u>

Testosterone (T) is a steroid hormone that has both androgenic and anabolic functions within the body, and is primarily responsible for growth of long bones during puberty and protein synthesis.[127] While numerous studies have shown increases up to 44% in T from pre- to post-competition,[128,129,130,131,132] T levels may be reduced following chronic exercise in absence of sufficient recovery. However, these potential fluctuations remain relatively unexplored and should be interpreted with caution in the case of women athletes.[133]

<u>Cortisol</u>

Cortisol (C) is a hormone released from the adrenal gland in response to physical and mental stress. It is one of the body's major glucocorticoids, meaning it is involved primarily with glucose metabolism. Thus, when there is inadequate glucose, cortisol mediates muscle breakdown so amino acids in muscle tissue can be used for energy, via gluconeogenesis. In absence of sufficient recovery, acute cortisol levels become a chronic issue, and are therefore used to assess excessive training fatigue and the onset of OT. High values signify the body's catabolic state and need for subsequent recovery. The increase in cortisol is often connected to the intensity and duration of exercise performed[134] and has shown to increase by 35% and 54% following anaerobic and aerobic exercise, respectively, in men.[135]

Testosterone-Cortisol Ratio

Intense frequent exercise leads to increased cortisol and reduced testosterone. Aldercreutz et al. proposed the use of T:C ratio as a diagnostic or preventive test to detect overtraining. The ratio provides information in regard to the anabolic-catabolic balance in response to training.[136] Thus, a higher ratio – indicative of elevated testosterone (T) and reduced C – suggests anabolism and a positive stress adaptation, while a depressed ratio – indicative of reduced T and elevated C – suggest catabolism and a negative stress adaptation. A decrease in T:C by >30% suggests insufficient hormonal balance and the onset of overreaching.[136] The T:C is particularly useful to monitor during an athletic season or competitive period to understand chronic anabolic-catabolic responses to training load imposed on the athletes, as it is expected to decline in response to intensified training.[137,138] However, fewer studies exist that measure long-term assessments throughout these critical periods for athletes.

Cytokines

Intense or prolonged bouts of exercise can lead to the production and subsequent elevation of cytokines. In particular, IL-6, IL-1, and TNF are cytokines that promote system inflammation,[34,139] muscle protein breakdown, and decreased appetite.[140] During periods of overreaching, these cytokines may reach chronically elevated levels due to extensive muscle damage resulting from intensified training demands.

Immunological

Salivary Immunoglobin A (sIgA) plays an important role in host defense, fighting against viral pathogens that enter the body and cause upper respiratory tract infections (URTI).[139] Intense exercise has shown to temporarily reduce sIgA production levels. Additionally, URTI incidence rates have been preceded by decreases in sIgA concentrations.[141,142] When exercise is repeated frequently, there may not be sufficient time for the immune system to fully recover, thereby making the athlete susceptible to infection.[143] Therefore, it may be expected that reduced levels of sIgA are prevalent in overreached athletes;[143] yet current research is minimal examining this relationship in collegiate athletes throughout their season and has shown mixed relationships to occurrence of illness.

Creatine Kinase

Creatine Kinase (CK) is an index of muscle damage, and is a likely cause for the reduction in exercise performance and increase in soreness associated with OT.[143] Rises in CK also impair the restoration of muscle glycogen, thus representing a decrease in subsequent performance due to less uptake of blood glucose.[143] While CK alone may not be best for measuring a state of OT, it may provide insight in regard to muscle damage and temporary overreaching states.[143]

Acute Assessments of Hormonal Responses to Competition

Testosterone, Cortisol, and the Testosterone-Cortisol Ratio

T, C, and the T:C are commonly altered immediately post-competition in men athletes from the following sports: rugby,[144,145] taekwando,[146] endurance cycling[147] and running,[148] soccer,[149,150] basketball,[129] football,[151] golf,[152] rowers,[153,154] wrestling,[155,] and swimming. The hormonal response in women athletes is understudied, with only limited studies examining these responses in women soccer[156] and endurance athletes.[133]

Studies have reported 1.5-2.5x higher salivary C post-competition compared resting values in elite soccer and rugby athletes,[144,150] in addition to a 62% reduction T:C.[144] These altered values indicate a substantial catabolic effect that follows sporting games. The adrenal response is also stronger for intermittent anaerobic sports versus continuous endurance sports.[157,158] Therefore, sports like soccer, basketball, football, wrestling, and lacrosse may exhibit larger hormonal imbalances due to the high intensity nature of the events, compared to steady state endurance athletes.

C and T:C values have shown to return to resting levels between 2 and 5 days post-competition; however, recovery is most likely dependent upon the intensity associated with the exercise.[144,145,159] Therefore, a 2- to 5-day recovery period appears to be a minimal duration between two sport competitions to allow for optimal recovery for athletes. Higher intensity and higher volume training sessions may require a longer subsequent recovery period to reestablish sufficient anabolic-catabolic balance.[144,145,159] In high level athletics, athletes are often required to compete within 24-72 hours of each other, making periodization and proper programming essential to prevent injury and NFOR and OT from developing.

The T response is less convincing. There is reason to believe sex differences may drive hormonal differences between men and women athletes due to women producing 5-7x less testosterone than mens.[142] In turn, this may affect cortisol production in women differently than in men, and more research is warranted that examines T in women athletes. While Edwards et al. showed a 37.5% increase in salivary T from pre- to post-game in collegiate women soccer players ($p<0.01$),[131] Lac and Berthon showed no change in salivary T in sub-elite women endurance runners following competition.[148] Interestingly, T has been shown to fluctuate following sporting games in response to a win or loss, as well as social connectedness to teammates, in both men and women athletes.[131,160] The evidence supporting salivary T in response to training load is less compelling and should be analyzed in addition to other biochemical markers to understand anabolic-catabolic balance.

Further, studies have examined hormonal responses by ‘starters’ vs. ‘non-starters.’ Current evidence supports that ‘starters’ elicit larger hormonal responses to single matches, most likely due to the differences in intensity and volume exposure in each group.[111] Women soccer starters showed steeper increases in salivary cortisol (pre-game: 18 nmol/L; post-game: 53 nmol/L; +250% rise) than non-starters (pre-game: 12.5 nmol/L; post-game: 28.8 nmol/L; +150% rise).[156] Following competitions, therefore, starters may need additional recovery compared to non-starters. It is recommended that coaches consider separating athletes for post-competition recovery practices to ensure all athletes receive sufficient recovery.

Biomarkers of Muscle Damage

When athletes do not receive adequate recovery time following an increase in training load, there is an increased risk of illness due to increased cytokine response.[161] Cytokine IL-6 and TNF are heavily involved in inflammation and infection processes in response to acute exercise, and has been used as a marker of inflammation and infection in professional men athletes.[161] Soccer, compared to basketball, volleyball, and handball, showed a 3-4x increase in IL-6 and TNF immediately post-game. In addition, CK was 2-3x higher in soccer players than other sports, indicating a soccer match showed the greatest inflammation and muscle disturbance.[161] This is most likely due to the physical demands associated with the sport of soccer. It requires a high exercise intensity be sustained over long periods (i.e. two 45-minute halves), which results in glycogen depletion.[161] Increases in CK were present in elite rugby,[162] collegiate football,[163] and elite handball athletes[164] following competition games. Rugby forwards elicited stronger CK changes most likely due to the differences in position-specific demands,[162] and CK has shown to increase up to 72% at 24 hours post competition and continue to be elevated up to 38 hours.[164,165] While most research observes increases in CK, Montgomery et al. saw only small magnitude changes after a basketball game.[166]

Further, peak concentrations of IL-6 occurred immediately post-game and were significantly higher than those values at 14 and 38 hours post-game. IL-6 levels have been shown to increase by 66% immediately following an elite handball competition[164] and showed large effect size changes from pre- to post-game in basketball athletes.[166] IL-6 responses were similar in women soccer athletes from pre-game (2.1 ± 0.8 pg/mL) to post-game (11.3 ± 3.7 pg/mL) ($p<0.05$).[167] Despite the high concentrations elicited following sport training and its relationship to illness, research across sport level and sex is limited. High secretion concentrations of IL-6 may be associated with heightened risk of upper respiratory tract infections, therefore, monitoring the cytokine response is recommended for athlete health.

Immunological

Despite the potential monitoring role sIgA may have, research assessing levels in athletes remains limited. Salivary immunoglobin A decreased after completion of high intensity training period compared to a low intensity period in elite men soccer athletes.[168] Significant reductions were also evident in professional men basketball players (range: 142.9 ± 22.7 – 210.7 ± 15.0; $F=7.48$; $p = 0.004$).[169,170] Salivary immunoglobin A has been inversely correlated with weekly training volume ($p<0.001$) in men and women swimmers, despite a low effect size ($r=-0.15$).[171] However, other studies have showed either no change in sIgA,[172] an increase in sIgA,[173] or no relationship between sIgA and upper respiratory tract infection symptoms.[174]

<u>Longitudinal Assessments of Hormonal Responses to Competition</u>

Testosterone, Cortisol, and the Testosterone-Cortisol Ratio

While the aforementioned data provide useful information in regard to an athlete's stress response to a single bout of competition, much less is understood about the athlete's response over a competitive season or period. A 14-week study in elite women swimmers reported serum C concentrations were lower in T2 (week 3) compared with T1 (baseline), but increased in T3 (week 10) and T4 (week 14); the T:C did not change.[175] Elite women volleyball players were assessed four times (i.e. September, November, January, May) over their competitive season and T:C decreased by 30% across measures ($p=0.009$), before returning to baseline levels.[176] Additional research is needed from a wide variety of women's sports and varying competitive levels in order to create hormonal reference values.

C and T:C have both shown varying fluctuations across four time points in professional men soccer players throughout their season.[128,177,178] Filaire et al. reported minimal non-significant changes in salivary C from T_1 (July) (13.02 nmol/L (1.3)) to T_2 (October) (13.77 nmol/L (0.9)) to T_3 (November) (15.33 nmol/L (1.1)) to T_4 (March) (13.65 (0.9)).[128] The peaked cortisol at T_3 coincided with a significant ($p<0.05$) reduction in T:C to 19.8 (2.6) (range: 19.8 – 30.3).[128] Renato Silva et al., however, reported lowest serum C at T_3 (90.5 ± 41.3 ng/mL; range: 90.5 – 176.5 ng/mL (T_1)), which coincided with the end of the season.[178] Therefore, athletes may have been insufficient at recovering throughout the season due to increased training volume and/or intensity. T:C was elevated at T_2 (4.7 ± 1.9) and T_3 (8.6 ± 5.3), and returned to baseline values (T_1) by T_4 (4.6 ± 1.7).[177]

Kraemer et al. (2004) assessed hormonal changes in 25 men collegiate soccer players throughout their season and analyzed T and C differences by starting status.[179] Athletes were assessed via blood draw during pre-season (T1) and five times throughout their season (T2-T6). T significantly increased by T6 in both starters (range: 12.25 – 17.20 nmol/L) and non-starters (range: 13.95 – 18.20 nmol/L) ($p<0.05$).[121] Concentrations of C were elevated in both groups at T1 (non-starters: ~660 nmol/L; starters: ~540 nmol/L), and at T4 (non-starters: ~650 nmol/L; starters: ~630 nmol/L), with both groups remaining elevated at T6 (non-starters: ~600 nmol/L; starters: ~600 nmol/L).[179] The T:C ratio was found to change during the season in the non-starters, with significant elevations reported at T6 (~0.032, $p<0.05$).[179] No changes were observed in starters. Further, these data indicate that players entering the season with low T and increased C may not be able to fully recover to resting concentrations, thus compromising performance. The pre-season window, therefore, is of particular concern because training loads are typically 2-4x greater than in-season loads[180] and if athletes are unable to recover entering the season, they are at higher risk of injury and OT. Yet, the pre-season window remains understudied and little is known about the biochemical and physiological demands during this time.

McFadden et al. and Walker et al. found men[181] and women[182] collegiate soccer athletes experienced an elevation in serum cortisol from pre-season throughout the season (ΔC: 0.34 ± 0.1 mcg/dL, $p < 0.05$), and returned to baseline levels by week 10 of the season.[182] T increased from pre-season to week 2 of the regular season in women soccer players (T: 39.5 ± 17.3 ng/dL, $p<0.05$) and returned to baseline by week 10.[182] Creatine kinase increased from pre-season to week 2 of the regular season (ΔCK= 204.9 ± 90.3 U/L, $p < 0.05$) before returning to baseline for womens and increased from pre-season to middle of in-season (ΔCK: 141 ± 57.1 U/L, $p < 0.05$) for mens.[181] While there was no change in T:C throughout the season, the increase in C demonstrates an elevated stress response, which was pronounced for women. This may indicate womens respond differently to training load and thus an individualized approach is needed. Hormonal responses vary widely and more attention should be given to this relationship in women athletes.

Metabolic Mechanisms

Paradoxically, both optimal training and OT induce a directional shift to the right on the lactate curve,[183] making it difficult to interpret training status solely from lactate values. Decreases in lactate in response to intensified training demands results from an improvement in lactate utilization, whereas decreases in lactate in response to OT suggest a decreased capacity of the muscle to produce lactate.[183] Therefore, to help differentiate training from OT, Snyder et al. suggested complementing lactate with rate of perceived exertion (RPE) to create a lactate:RPE ratio.[184] A decrease in blood lactate followed by an increase in RPE is indicative of an OT state, while an unchanged RPE with decreases in blood lactate indicate training adaptations. The lactate/RPE quotient, therefore, would be expected to decrease with OT, but remain the same with training adaptations.[184] However, it was later suggested that this ratio may more accurately reflect glycogen depletion than an overtrained state.[184] To prevent misinterpretation of lactate due to glycogen depletion, it is advised to look at anaerobic threshold (AT). AT is not affected by glycogen depletion and as such, a reduced AT is more indicative of optimal training adaptations.[185]

It has been further suggested to convert absolute blood lactate into a percentage of peak lactate.[185] If the right shift in the curve is maintained with the newly calculated percentage, the decrease in lactate would reflect an increase in lactate utilization and adaptation from optimal training.[185] If the shift is no longer present, the primary cause of the decrease observed in lactate may be attributed to the muscle's incapacity to produce lactate and would indicate performance decrements prompted by OT.[183]

Lactate alone may not be a sufficient marker to determine OT status because it is heavily influenced by extraneous factors. In addition to glycogen depletion, lactate is influenced by the rate of change in exercise intensity, the mode of exercise, menstrual cycle, ambient temperature, and muscle damage. Rapid increases in exercise intensity,[186] the larger the mass of the recruited muscles,[187] presence of menstrual cycle,[188] warm temperatures,[189] and high eccentric movements leading to soreness[190] all increase blood lactate levels, skewing values from reliably reflecting training status. Further, it may not be practical in a sport setting, as it would require athletes to sit quietly for 5 minutes post-training and have several researchers available to collect such data. Plus, not all athletes are exposed to the same training demands at during sessions, and may be better utilized following max testing during pre and post seasons.

Due to its paradoxical relationship, many researchers do not monitor lactate as a measure of load and thus, little is actually known about its role as a load marker. Lactate measured with sleep, mood, and performance results may be a more comprehensive measure of OT so recovery status is distinguished from enhanced aerobic fitness and adaptation.[185]

Self-Assessment Mechanisms

While a wide range of objective markers exists for monitoring OT, self-assessment measures, including mood, rate of perceived exertion, wellness (i.e. fatigue, soreness, stress), and sleep, should not be undervalued.

Mood is commonly measured using the Profile of Mood States (POMS),[191] which analyzes six dimensions of mood (tension-axiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment) based on a 5-point Likert scale from 0 (*not at all*) to 4 (*extremely*). However, the sale is long (65 items) and time consuming (>10 minutes), and thus may not be practical or well-accepted by athletes in a time-restricted sport setting.[192] Shorter versions exist (POMS-B)[193] that contain fewer items, but administration time is still long for use in high level sporting environments.[192]

It is recommended that mood scales take less than 1 minute to complete to ensure long-term adherence.[192] The Brief of Assessment of Mood (BAM)[194] is a six-item scale that asks participants to rate their anger, tension, depression, vigor, fatigue, and confusion on a scale of 0 (*not at all*) to 4 (*extremely*). The BAM has shown to correlate highly with the full version of the POMS,[195] indicating its validity with the original mood measure. In addition to mood, Likert scales assessing soreness, energy, stress and fatigue may provide useful insight into self-perceived load responses.

Session rating of perceived exertion (sRPE = rating of perceived exertion (sRPE) x duration of session) is another reliable and valid measure to subjectively assess load.[196,197,198–200] Athletes rate their perceived level of exertion on a scale from 0-100 or 0-10 either using the Borg CR-100 or CR-10 scale, respectively. Correlations between both scales and between-changes scores were nearly perfect (r=0.95 and r=0.91–0.98),[201] indicating either scale may be an appropriate tool to include when monitoring training load.[198] RPE should be collected approximately five minutes post-session to avoid a 'recency effect' from occurring.[202] That is, if athletes finished a session with sprints, their RPE should not be reflective of the sprints, only, but rather of the session in its entirety.

The use of athlete self-report measures in the form of brief wellness questionnaires provide a convenient and effective means of monitoring an athlete's perceptual response to training.[203] Decrements in wellness are strong indicators of a maladaptive training response that have been associated with overtraining.[11] There are a few number of established sport-specific psychometric questionnaires to assess athlete training status, including the Recovery-Stress Questionnaire (REST-Q),[204] Recovery-Cue,[205] Athlete Burnout Questionnaire,[206] Daily Analysis of Life Demands for Athletes (DALDA),[207] and Athlete Distress Questionnaire.[208] However, these tools are considered too lengthy and impractical for daily use, particularly in team sport athletes.[209] Therefore, practitioners have been encouraged to customize questionnaires into their morning routine.[11,116] Individualized questionnaires should assess fatigue, soreness, stress, and energy, on Likert scales from 1-7 for quick results.[210,211,212] This provides immediate and valuable information in regard to the athlete's psychometric condition prior to training, which coaches may interpret and adjust subsequent sessions as necessary.[211]

While it may seem obvious to most, sleep is re-emerging as a monitoring tool for OT. Sleep deprivation may be detrimental to the outcome of the recovery process after a game, resulting in impaired muscle glycogen repletion, impaired muscle damage repair, alterations in cognitive function and an increase in mental fatigue.[213] Sleep quantity and quality declines following augmented increases (+30%) in training load,[214] and poor sleep is a common complaint among overreached and/or overtrained athletes.

Self-Reported Measures and Sport Performance

In elite men rugby players, the relationship between mood and performance remains inconclusive. While Shearer et al. showed mood, as measured by the BAM, was inversely correlated with power (r=-0.34, p=0.02),[192] West et al. showed results from the BAM had no effect on peak power output (p=0.321) or jump height (p=0.133) in elite men rugby athletes.[215] Elite level men soccer athletes showed higher levels of depression,[128,216] anger,[216] and tension,[128] and decreases in vigor[128,216] (POMS) were associated with performance decrements as measured by interval shuttle run tests[216] and winning percentages.[128] Hamlin et al. (2019) also reported lower levels of mood were able to successfully predict injury (OR: 0.89) in 182 men and women collegiate athletes from a variety of sports.[217]

Players' wellness can be a useful tool, ideally used within a broader monitoring scheme, for monitoring ongoing muscular fatigue and exertion levels at practice.[218,219,220] For example, very large (r = 0.7–0.89) to large (r = 0.5–0.69) correlations were identified between wellness and countermovement jump (CMJ) variables (positive association: velocity, dip, time; negative association: duration), and each wellness subscale (general fatigue, upper body soreness, lower body soreness, sleep quality, and sleep quantity) displayed large to very large positive correlations with CMJ velocity in professional men rugby athletes. Further, pre-practice fatigue, soreness, stress, and energy have been associated with RPE and EL measures (i.e. TD, PL, HSD, accelerations) during the subsequent training session.[218,221]

The relationship between sleep quality, mood, and sport outcome performance (i.e. winning vs. losing) was assessed in a large sample of men (n=404) and women (n=172) elite athletes from a variety of individual and team sports.[222] Evaluations were performed 60 minutes prior to the start of the sports event, and results revealed that sleep quality, anger, tension, and vigor predicted athletes' performance. In particular, poor sleep quality and low vigor and anger decreased the odds of winning, whereas high tension increased the odds of winning.[222] In fact, 88.2% of losing cases and 19.2% of winning cases could be predicted by sleep quality, vigor, anger, and depression, compared to 61% and 26%, respectively, found in prior literature examining collegiate athletes.[223] Therefore, mood may adversely affect performance to a greater extent than positively affecting performance.

In contrast, however, Andrade et al. reported high tension was moderately associated with losing competition ($p<0.01$, $d= 0.49$) in men and women elite volleyball players.[224]

In addition to sport outcome performance, collegiate men basketball athletes, who demonstrated greater durations of sleep, had faster sprint times (15.5 ± 0.54 sec vs. 16.2 ± 0.61 sec, $p< 0.001$), improved free throw percentage (+9%, $p<0.001$), and 3-point throw percentage (9.2%, $p<0.001$).[94] A recent study found that decreased sleep mediated the negative effect of training load on mood (26.8%, $p<0.001$), fatigue (12.6%, $p<0.001$), and stress (24.5%, $p<0.001$).[225] Thus, the impact of training load on well-being is exacerbated by reduced sleep and minimized by increased sleep. This suggests that efforts to prioritize sleep, particularly during periods of high acute training load, may help reduce the negative impacts upon well-being and even potentially reduce the risk of injury and illness.

Therefore, inquiring about sleep patterns may provide insight as to how athletes recover. The role of sleep in recovery is a complex issue, reinforcing the need for future research to estimate the quantitative and qualitative importance of sleep and to identify influencing factors.[226] It is understood that coaches may be hesitant to use self-reported measures as they fear their athletes will not be truthful in responding. However, research has shown the benefit that these simple and quick scales can provide to practitioners in regards to future athlete performance and health.[227,228]

External + Internal Load

In order to understand comprehensively an athlete's exposure to load, studies must examine the relationship of EL and IL in combination. If only EL is analyzed, no information in regard to the stress response is provided. Athletes respond differently to load, therefore, it cannot be assumed that two athletes performing the same volume and intensity of work that will respond in a similar pattern to IL measures. At the same time, it is not sufficient to look solely at IL, because no justification in regard to the changes in stress levels is provided. Stress may result from a variety of avenues (i.e. exams, relationships, workload, etc.), and without EL, the stimulus that triggered the response cannot be determined. Thus, EL should be combined with IL to comprehensively understand an athlete's response to training. However, limited studies exist that examine a variety of these measures in combination.

Relationship Between External Load and Physiological Measures

As seen in Table 4, the six studies examining EL measures and the relationship to physiological adaptations, reported findings from predominantly elite, men athletes.[114,229,230] The relationships observed provide contrasting results, indicating the effect of volume and intensity measures from GPS/GNSS devices have an unestablished relationship with resting lnRMSSD and post-exercise HRR. Since HR measures are quick and easy to obtain, more research in combination with EL systems may provide insight into interpretation of various HR markers in the absence of EL systems.

Table 4. Relationship between EL and physiological measures

Study	Sport	Sex	n	Level	Relationships
Beato et al.[231]	Futsal	F	16	Professional	Despite changes ($p<0.05$) in TD, RV, HSD, no change in mean HR(%Max) was seen ($p>0.05$).
Chrismas et al.[229]	Soccer	M	6	Elite	Relationships between lnRMSSD and distance, acceleration, and HSD were trivial (ES: <0.20); impacts, deceleration, and high metabolic load distance were small (ES: 0.21-0.60)
Flatt et al.[232]	Football	M	25	NCAA Division I	lnRMSSD_chronic was not related to PL_chronic or PLcv ($p>0.05$). Large relationship between lnRMSSDcv and PL_chronic, only ($r=-0.60$, $p<0.01$). No daily relationships were found.
Flatt et al.[233]	Football	M	27	NCAA Division I	Large reduction in lnRMSSD was associated with lower PL ($r=0.464$, $p= 0.015$). No relationship between RHR and lnRMSSD ($p>0.05$).
Plews et al.[230]	Rowers	M	9	Elite	Small relationship between total training time and lnRMSSD (ES=0.37)
Thorpe et al.[114]	Soccer	M	10	Elite	Fluctuations in lnRMSSD was associated with fluctuations in HSD ($r=-0.27$, $p=0.04$). HRR and HSD were not associated ($p>0.05$).

TD: total distance; RV: running velocity; HSD: high speed distance; PL_chronic: weekly player load; PLcv: coefficient of variation for player load; lnRMSSD_chronic: weekly lnRMSSD; lnRMSSDcv: coefficient of variation for lnRMSDD; HRR: heart rate recovery; ES: effect size

Relationship Between External Load and Hormonal Measures

Limited data exist that assess the impact of EL measures on biomarker secretion (Table 5). The studies examining this relationship reported findings from professional[234] and elite men athletes.[145,235] With the discrepancy between men and women athletes, further research is necessary to view the sex-difference responses, particularly in collegiate athletes who are faced with a multitude of stressors.

Table 5. Relationship between EL and hormonal measures

Study	Sport	Sex	n	Level	Relationships
Jones et al.[234]	Rugby	M	28	Professional	Changes in CK associated with tackles (ES=0.579, p<0.001), contact hits (ES=0.518, p<0.001), total impacts (ES=0.638, p<0.001) sprint number (ES=0.339-0.419, p<0.05), distance sprinting (ES=0.409-0.420, p<0.05), and HSD (ES=0.434, p<0.05).
McLellan et al.[145]	Rugby	M	17	Elite	TD was not associated with plasma CK (r=0.28, p>0.05), or salivary T (r=-0.07, p>0.05), C (r=0.09, p>0.05)
McLellan et al.[235]	Rugby	M	17	Elite	Number of hit-ups in impact zone 4 (p=0.036-0.041), zone 5 (p=0.009-0.040), and zone 6 (p=0.005-0.041) was associated with plasma CK, but not serum C (p>0.05).
Thorpe and Sunderland[236]	Soccer	M	7	Semi-professional	Plasma CK was correlated with sprint number (r=0.80, p=0.029) and sprint distance (r=0.78, p=0.039). Percent increase in CK was correlated with sprint number (r=0.86, p=0.014), sprint distance (r=0.89, p=0.007), and HSD (r=0.92, p=0.004). MYO was correlated with sprint number (r=0.76, p=0.047). T, C, and IgA were not correlated with sprints (p>0.05).

M: men; F: women; CK: creatine kinase; HSD: high speed distance; MYO: myoglobin; T: testosterone; C: cortisol; IgA: salivary immunoglobin A

Relationship Between External Load and sRPE and TRIMP

Due to the ease and popularity of measuring sRPE and TRIMP, researchers have examined their relationship to EL measures. Thirteen studies assessed relationships in men athletes at professional levels, and one study[237] reported values from a men's collegiate sports team (Table 6). Meta-analyzed relationships between internal and external measures of load show that sRPE has a stronger association than TRIMP to many EL dimensions (TD, HSD, impacts, and acceleration) (Table 7).

Table 6. Descriptive table of studies comparing internal measures of sRPE and TRIMP to EL (adapted from McLaren et al., 2018[238])

Study	Sport	Sex	n	Competitive Level	IL	EL
Bartlett et al.[239]	Australian Football	M	41	Australian Football League	sRPE	TD Distance covered > 14.4 km h^{-1}
Casamichana and Castellano[240]	Soccer	M	14	Spanish Regional	sRPE	Relative distance, relative distances, and frequency of efforts > 18.0 and > 21.0 km h^{-1}, accelerometer load
Casamichana et al.[241]	Soccer	M	28	Spanish Third Division	sRPE	TD, distances and frequency of efforts > 18.0 and > 21.0 km h^{-1}
Gallo et al.[242]	Australian Football	M	39	Australian Football League	sRPE	TD, TD covered at individualized high speeds, total and low velocity (< 7.2 km h^{-1}) accelerometer load
Gaudino et al.[243]	Soccer	M	22	English Premier League	sRPE	TD covered > 14.4 km h^{-1}, total number of impacts (> 2 G), total number of accelerations (> 3 m s^{-2})

Lovell et al.[244]	Rugby	M	32	National Rugby League	sRPE TRIMP	TD, TD covered at speeds > 15.0 km h^{-1}, total accelerometer load[e], total number of impacts (> 5 G)
Pustina et al.[237]	Soccer	M	20	NCAA Division I	sRPE	TD covered, TD covered at speeds > 14.4 km h^{-1}, accelerometer load
Scanlan et al.[245]	Basketball	M	8	Australian 2nd Tier	sRPE TRIMP	Total accelerometer load
Scott et al.[149]	Soccer	M	15	Australian A-League	sRPE TRIMP	TD covered, TD covered and time spent at speeds < 14.4, ≥ 14.4, and ≥ 19.8 km h^{-1}, accelerometer load
Scott et al.[198]	Australian Football	M	10	Australian Football League	sRPE TRIMP	TD covered, TD covered at speeds ≥ 13.1 km h^{-1}, total accelerometer load
Weaving et al.[246]	Rugby	M	17	English Super League	sRPE TRIMP	TD covered > 15 km h^{-1}, total number of impacts (> 5 G), total accelerometer load

Weaving et al.[247]	Rugby	M	23	English Championship	sRPE TRIMP	TD covered at individualized high speeds, total accelerometer load
Weston et al.[248]	Australian Football	M	26	Australian Football League	sRPE	TD, TD covered at speeds < 14.4 and ≥ 14.4 km h^{-1}, total tri- and bi-axil accelerometer load[c], TD covered at high instantaneous metabolic power (> 20 W kg^{-1}), equivalent TD covered for steady-state running, average metabolic power, estimated energy expenditure

M: men; F: women; sRPE: session Rate of Perceived Exertion; TRIMP: training impulse; TD: total distance

Table 7. Meta-analyzed relationships between internal and external measures of load and intensity in team-sport athletes during training and competition (adapted from McLaren et al., 2018[238])

Internal Measure	External Measure	Number of Studies	Pooled Effect r (90% CI)	Inference
sRPE	TD	6	0.79 (0.74-0.83)	Possibly very large

	HSD ≥ 13.1–15.0 km h^{-1}	6	0.47 (0.32-0.59)	Likely moderate
	VHSD ≥ 16.9–19.8 km h^{-1}	4	0.25 (0.03-0.45)	Unclear
	AL	9	0.63 (0.54-0.70)	Likely large
	Impacts > 2–5 G	3	0.57 (0.47-0.64)	Possibly large
TRIMP	TD	2	0.74 (0.56-0.86)	Not possible
	HSD ≥ 13.1–15.0 km h^{-1}	2	0.28 (0.10-0.45)	Unclear
	VHSD ≥ 16.9–19.8 km h^{-1}	3	0.17 (-0.04-0.36)	Unclear
	AL	5	0.54 (0.40-0.66)	Possibly large

sRPE: session RPE; TD: total distance; HSD: high speed distance, VHSD: very high speed distance; AL: accelerations

Relationship Between External Load and Wellness Measures

Findings from research that examined the relationship between EL and wellness measures remains inconclusive (Table 8). Some authors report wellness, fatigue, and soreness as correlates and predictors of PL,[211,221,249,250] TD,[250–253] and HSD,[249,251,252] while others report no association[211,221,251,254,255] between measures. Further, only one study reported women athletes,[256] and only one reported collegiate athletes.[256]

Table 8. Relationship between objective EL and wellness measures

Study	Sport	Sex	n	Level	Relationships
Gallo et al.[211]	Australian Football	M	36	Professional	Wellness z-score was associated with PL, only (R^2=0.57, p=0.002). No relationship was seen in average speed or HSD. Wellness z-score of -1 was associated with trivial reductions in average speed (d=0.26) PL (d=-0.45) and HSD (d=-0.25).
Govus et al.[221]	American Football	M	58	NCAA Division I	Wellness z-score was associated with a trivial increase (+2.3%) increase in PL (χ^2(1)=4.40, p=0.04)) Pre-training energy was associated with a trivial (+2.6%) increase in PL (χ^2(1)=3.03, p=0.08) No relationship between soreness (χ^2(1)=1.81, p=0.18) or sleep (χ^2(1)=2.24, p=0.13) with PL
Jaspers et al.[249]	Soccer	M	26	Professional	Fatigue, soreness, and stress most predictive, although small, of PL, HSD (>20 hm r^{-1}) , accelerations (>1 m/s^2), and decelerations (<-1 m/s^2)
Lathlean et al.[257]	Australian Football	M	562	Professional	Mood, stress, and soreness associated with load throughout a 24-week season
Malone et al.[251]	Soccer	M	48	Elite	Reduced wellness score correlated with HSD (R^2=0.69, p=0.001), maximal velocity (R^2=0.59, p=0.045), and PL (R^2=0.45, p=0.015)
Malone et al.[254]	Soccer	M	1	Elite	Total wellness score was associated with total duration (r=-0.35, p<0.05), TD (r=-0.28, p<0.05), and deceleration (r=-0.27, p<0.05). No relationship was seen between acceleration, PL, or PL/min

Malone et al.[252]	Gaelic Football	M	22	Elite	Changes in wellness was associated with change in TD ($r=0.68$, $p<0.05$), HSD ($r=0.68$, $p<0.05$), but not sprint distance ($r=0.17$, $p>0.05$)
McGuiness et al.[256]	Field Hockey	F	16	Elite	Changes in sleep, soreness, and mood were associated with decreased HSD during games.
Thornton et al.[253]	Rugby	M	31	Professional	TD was moderately related to sleep quantity ($r=-0.31$, $p<0.05$), but not sleep efficiency ($r=0.04$, $p>0.05$)
Owens et al.[255]	Soccer	M	10	Elite	No relationship between energy, soreness, sleep, wellness with TD, THID, and FEHI ($p>0.05$)
Wellman et al.[250]	American Football	M	30	NCAA Division I	PL, LID, MID, TD, deceleration and acceleration distances was positively associated with soreness and stress ($p<0.05$). No differences in movement variables were demonstrated for subscales of mood and sleep quantity ($p>0.05$).

Low/medium intensity distance
Frequency of efforts at high intensity

Relationship Between Physiological and Wellness Measures

The seven studies assessing the relationship between physiological measures (HR, HRV, and HRR) and wellness are inconclusive in men and women, elite and collegiate athletes (Table 9). Some have reported significant associations between heart rate indices and sleep,[226,258] fatigue,[225,226] stress,[258] and soreness,[226] and others observed no apparent relationship[114,203] and suggested wellness as a more sensitive and predictive measure when compared to HRV.[259,260]

Table 9. Relationship between physiological and wellness measures

Study	Sport	Sex	n	Level	Relationships
Bisschoff et al.[261]	Badmitton	M	22	Elite	In match HRV and HRR was associated with muscle soreness (p=0.014). Pre-match and post-match HRV and HRR showed no significance.
Flatt et al.[258]	Swimming	M	17	NCAA Division I	RHR was lower with better sleep quality (p<0.001), less stress (p=0.02), and better mood (p=0.015). No associations between RHR and fatigue or soreness. lnRMSSD was higher with better sleep (p<0.001), lower fatigue (p<0.001), less stress (p=0.014), and better mood (p<0.001). No relationship between lnRMSSD and soreness.
Flatt et al.[226]	Soccer	F	8	NCAA Division I	No relationship between lnRMSSD and stress, or lnRMSSD and mood. Low correlation between lmRMSSD and sleep (r=0.34). Moderate correlations between lnRMSSD and fatigue (r=0.56) and soreness (r=0.54).
Flatt et al.[262]	Soccer	F	10	NCAA Division I	Higher lnRMSSDcv was associated with greater fatigue (r=-0.55). No relationship was observed with sleep quality, soreness, mood, or stress.
Rabbani et al.[260]	Soccer	M	9	Professional	Inverse moderate relationship between wellness and lnRMSSD (r=-0.41). Wellness was observed to be a more stable and sensitive measure than HRV when used to monitor match-induced fatigue
Rabbani et al.[141]	Soccer	M	8	Professional	Wellness indices are more predictive than lnRMSSD for sRPE (r=0.72 and r=-0.21, respectively).

Saw et al.[203]	Variety	M/F	56		No association between HRV and tension, depression, anger, confusion, and vigor (POMS). Negative association between RHR and tension, depression, anger, and confusion.
Thorpe et al.[114]	Soccer	M	10	Elite	No association between sleep quality, soreness, and HRR ($p>0.05$)

Relationship Between Hormone and Wellness Measures

Hormonal analysis is expensive and not readily accessible to most teams; therefore, it would be beneficial to explore other load markers that may be related to biomarker response as a potential viable alternatives. The limited number of studies that have assessed their relationship (Table 10), portray contrasting findings and thus, no clear understanding can be interpreted from the current body of research.[128,129,177,215,263–265] Further, these studies report results from only elite and professional level athletes, with two studying women athletes.[263,265]

Table 10. Relationship between hormone and wellness measures

Study	Sport	Sex	n	Level	Relationships
Broodryk et al.[263]	Soccer	F	47	Semi-professional	No correlations between salivary cortisol total mood disturbances (p>0.05)
Filaire et al.[177]	Soccer	M	20	Professional	No correlations between mood (POMS) and salivary T, C, T:C, and IgA (p>0.05)
Filaire et al.[128]	Soccer	M	17	Professional	No correlations found between salivary T, C, T:C and mood (POMS) (p>0.05)
Maso et al.[264]	Rugby	M	25	Professional	Overtraining questionnaire score associated with T, only (r=-0.70, p<0.01).
West et al.[143]	Rugby	M	14	Professional	No relationship between mood (BAM) and serum T (p=0.232), C (p=0.166), or the T:C (p=0.103).
Gonzalez-Bono et al.[129]	Basketball	M	16	Professional	Salivary C was associated with vigor (POMS) only in winners (r=0.79, p=0.02), no associations were found in losers.
O'Donnell et al.[164]	Netball	F	10	Elite	High salivary cortisol was related to reduced sleep quality (d=-0.79, moderate, p=0.018) and sleep quantity (d=-1.41, large, p=0.008).

Relationship Between Hormone and Physiological Measures

Only one study currently exists[267] that assessed the relationship between hormonal and physiological measures in sports teams, of which no relationship was observed (Table 11).

Table 11. Relationship between hormone and physiological measures

Study	Sport	Sex	n	Level	Relationships
Solana-Tramunt[267]	Swimmers	F	12	Elite	No correlation between change in lnRMSSD and change in salivary cortisol ($p>0.05$)

Summary

Overtraining results from intensified training without adequate recovery. In attempt to prevent OT, injury, and illness from developing, there are a variety of load monitoring strategies. Monitoring EL (physical work) and IL (physiological, biochemical, metabolic, and self-reported psychological measures) provide information in regard to training status. Through examination of EL, practitioners gain valuable data in regard to the physical work performed by athletes during practices and competitions, by sport-specific positions, and by time-course throughout a competition. Subsequently, monitoring their internal stress response reveals their autonomic function, anabolic-catabolic balance, inflammation and muscle damage status, metabolic regulation, and overall wellness state.

However, the current literature lacks analysis of comprehensive measures of training load (EL and IL in conjunction with one another) across a competitive window. While athletes may perform the same EL, their individual internal stress response is unique, indicating the importance of individualization in load monitoring. At the same time, sole monitoring of IL provides no justification of the stress response, and practitioners need that information to understand what work negatively impacted their athletes. Furthermore, minimal studies utilize high-level collegiate men and women athletes from varying sports teams, with no research examining women lacrosse players. Therefore, more research is needed that comprehensively examines the relationship among a variety of load variables in collegiate athletes. Understanding the relationship between EL and IL may assist in program development to ensure athletes are achieving sufficient bouts of recovery to optimize their health and sport performance.

Justification

This is what is known: When overload is not balanced with adequate recovery, athletes are at an increased risk of injury, illness, and NFOR/OT. EL provides information regarding the physical work incurred by the athlete during a training session and has shown a strong relationship to injury status. There are various markers of IL to assess stress response, including physiological, biochemical, subjective, and metabolic measures. Autonomic and anabolic-catabolic balance, as well as wellness and mood, have been shown to decline in response to acute bouts of exercise training in high-level male athletes. Blood lactate remains inconclusive as an adequate measure of training load status.

This is what is unknown: The literature has not thoroughly examined IL across collegiate women athletes from a variety of sports, particularly hormonal responses. With women lacrosse participation steadily on the rise and the intense demands associated with the sport, no studies have examined IL in this population. In addition, current research lacks comprehensive understanding of the relationships between EL and IL in collegiate athletes. Last, longitudinal assessments of load monitoring remains understudied and thus, little is known in regard to the impact of a competitive season on athletes' stress response. In particular, the pre-season window is less commonly examined, despite training loads being 2-4x higher than in-season periods.

This is how the dissertation will address the gaps: In order to address the major gaps in the literature, three manuscripts have been developed. In manuscript 1, IL was examined in women lacrosse athletes throughout their competitive season. IL measures included resting HRV (physiological), resting salivary T, C, and T:C (hormonal), and pre-training self-reported ratings of fatigue and recovery (subjective). All measures were collected weekly for 13 weeks to examine how the stress response changes throughout a full season. Manuscripts 2 and 3 investigate collegiate men soccer athletes throughout their 13-day pre-season period. Manuscript 2 evaluated the relationship and bi-directional predictability between EL and self-assessment scales (fatigue, soreness, stress, energy, sleep, mood). EL has shown to independently predict injury risk, and few studies indicate an association between EL and self-assessment scales. Therefore, if this relationship and predictability holds true, then self-assessment scales may be a viable and valid addition to load monitoring for athlete health. Manuscript 3 was a comprehensive analysis of all EL and IL measures to determine their relationships to one another in attempt to understand the best, and most predictive, measures for practitioners to utilize in their load monitoring programs. This manuscript included EL, resting HRV, exercise HR, resting salivary T, C, T:C, self-assessment scales (fatigue, soreness, stress, energy, sleep, mood), and sRPE. These manuscripts shed light on loading in different sports, different genders, and different competitive periods throughout a season.

Justification of Measures: These manuscripts utilize a variety of load monitoring measures, although not including all the measures discussed in this dissertation. A strength of this project is the field-based study, where athletes are not restricted to stringent laboratory settings. However, with field studies, measurements must be easy and practical in order to administer to a large group of athletes simultaneously and efficiently and not interrupt athletes' busy schedules. Therefore, all biochemical analyses performed were assessed in saliva, as these measurements were taken daily, as blood assessment would have been more invasive and time consuming. Thus, the study was limited to T, C, and T:C, despite other markers of muscle damage relating to load monitoring. The nature of field studies dictated the methods and specific measures obtained.

CHAPTER 3: STUDY 1

Internal Training Load Measures During a Competitive Season in Collegiate Women Lacrosse Athletes

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ABSTRACT
Monitoring internal load provides useful and non-invasive markers of training stress and adaptation. However, the relationship between internal load measures across a competitive window remains inconclusive and limited. The purpose of this study was to report various internal load measures, as well as their relationship, across a season in Division I women lacrosse athletes (n=20). Ultra-short natural logarithm of the root mean square of successive differences (lnRMSSD), salivary testosterone, cortisol, the testosterone:cortisol ratio, and self-reported measures of fatigue and recovery were collected weekly for 13 weeks. Means ± SD were calculated to provide descriptive values and a repeated measures analysis of variance (ANOVA) was used to analyze changes in testosterone, cortisol, testosterone:cortisol ratio (n=8), and lnRMSSD (n=8) over the course of the season. Pearson correlations assessed relationships between all internal load measures. No significant time effect was observed in testosterone (p=0.059), cortisol (p=0.544), testosterone:cortisol ratio (p=0.120), or lnRMSSD (p=0.062). lnRMSSD was correlated with testosterone (r=0.265), cortisol (r=-0.232), testosterone:cortisol ratio (r=0.345), and fatigue (r=-0.256) (p<0.05). More research is needed to examine relationships among markers of internal stress across all phases of the training cycle. Routine monitoring may help practitioners optimize training programming to reduce injury, illness, and overtraining.

KEY WORDS: athlete monitoring, internal stress, lacrosse

INTRODUCTION

A primary goal of training for sport is to enhance performance. Progressive overload, defined as the gradual increase of stress on the body during exercise, has been shown to elicit training gains. However, a balance between periods of overload and recovery must be achieved if adaptations are to be engendered and overtraining prevented (16). It is the internal stress that provides a quantification of an athlete's training response to a given stimulus and should be a major consideration when monitoring athlete load (17). There are currently 375 National Collegiate Athletic Association (NCAA) women's lacrosse programs with participation increasing steadily since 2001 (24). Despite its popularity and the high physical demands associated with the sport, no studies have examined training load responses in women's collegiate lacrosse.

Lacrosse has been described as the "fastest game on two feet" and is considered one of the most strenuous women's team sports (29). The game involves two halves lasting 25-30 minutes, each, and requires quick transitions with abrupt changes in speed and direction, continuous activity, and high-intensity sprints up and down the field over a long duration. Therefore, lacrosse elicits the involvement of both aerobic and anaerobic energy systems, with collegiate women players averaging a VO_{2max} of 42.8 ± 4.4 ml $kg^{-1} \cdot min^{-1}$ (9,29,33). The sport's physical demands tax the cardiovascular, muscular, and endocrine systems (9,29). However, research is needed to explore the stress response associated with these high demands.

There are several markers that are used to quantify an athlete's internal stress response to a given training stimulus, including physiological, hormonal, and self-assessment scales.

Resting heart rate variability (HRV), as measured by the natural log root mean square of successive R-R intervals (lnRMSSD), has been suggested as an effective tool for monitoring fitness and recovery status due to its non-invasive and time efficient nature (7,11). Additionally, the testosterone (T) to cortisol (C) ratio (T:C) provides information in regard to the anabolic-catabolic hormonal balance in response to training. Since women produce 5-to-7 times less T, it is believed C responses may differ from those of their male counterparts (3). Thus, specific research toward these hormonal responses to training specifically in women athletes are needed. In addition, there are many objective markers for monitoring training load, yet the value of self-assessment scales should not be underestimated. High levels of fatigue and poor ratings of recovery have been related to sport performance (3,5), but little is known about their relationship to physiological and hormonal markers.

Internal training load markers have been measured on a limited basis in women collegiate athletes, with no data reported on women lacrosse athletes. In women collegiate soccer athletes, changes in lnRMSSD were positively associated with changes in fatigue and soreness across a pre-season window (14). In addition, starters demonstrated a significantly steeper increase in C in response to competitive season play compared to non-starters (18). Soccer and lacrosse share similar characteristics, as both are intermittent field sports and have similar positional identities (e.g., forwards/attackers, midfielders, defenders), yet distinct differences between sports do exist (9). For example, lacrosse defenders and attackers are restricted to particular areas on the field, and thus are likely to cover less distance at a higher movement speed (4,25). Further, inverse relationships between lnRMSSD and fatigue have been reported in elite male swimmers and endurance athletes, while fatigue has inconclusive associations with T, C, and T:C values across a variety of athletes (20,27).

Consistent load monitoring, particularly over a competitive season, may aid in determining athletes' stress responses to a given training stimulus in order to enhance sport performance, improve overall health, and reduce the risk of injury and overtraining. To date, no studies have examined seasonal internal loads within this population.

Therefore, the purposes of the current study were to 1) monitor resting hormonal and physiological responses across a competitive season in National Collegiate Athletic Association Division I (NCAA-DI) women lacrosse athlete and 2) determine the relationship between measures of hormonal, physiological, and self-assessments of fatigue and recovery. We hypothesized 1) the lnRMSSD and T:C would decline throughout the competitive season and 2) the lnRMSSD, T:C, fatigue, and recovery would be related.

Methods

Participants

Women collegiate lacrosse athletes (n=20, aged 18-24) from NCAA-DI, which is the highest level of American collegiate sport, participated in the study (Table 1). All athletes were under the direction of a strength and conditioning coach and were following sport-specific training regimens with neuromuscular demands particular to their respective sport and training program. Furthermore, nutritional programming was provided by the

University's registered sports dietitian. All participants completed a medical history form and had been cleared previously for intercollegiate athletic participation. Risks and benefits were explained to athletes and an institutionally approved consent form was signed prior to participation. The Institutional Review Board for Human Subjects approved all procedures and followed all principles outlined in the Declaration of Helsinki.

Table 1. Participant descriptive characteristics (n=20)

Position	
Goalie	3(15)
Defender	6(30)
Midfielder	6(30)
Attacker	5(25)
Academic Year	
Freshman	8(40)
Sophomore	2(10)
Junior	6(30)
Senior	4(20)
Race	
White	15(75)
Black	2(10)
Asian	1(5)
Other	2(10)

Values are presented as n(%)

Protocol

Measurements were obtained weekly throughout the 13-week lacrosse season, which extended from the end of January to the beginning of May. Depending upon the number of weekly games, lacrosse practice was held between three and six days per week (Monday–Saturday) and lasted approximately two hours in duration. Between one and three competition games were played each week. Resting HRV and self-assessments of recovery and fatigue were obtained across 13 weeks, while salivary T and C were obtained across 11 weeks (Figure 1). All measurements were obtained in the morning (~10:50am), prior to the team's scheduled practice time (11am-1pm).

Seventeen total games were played throughout the study as follows: 0 games during weeks 1-3 (pre-season); 1 game in week 4; 0 games in week 5; 2 games in week 6; 3 games in week 7; 2 games in week 8; 2 games in week 9; 2 games in week 10; 2 games in week 11; 2 games in week 12; and 1 game in week 13 (Figure 1).

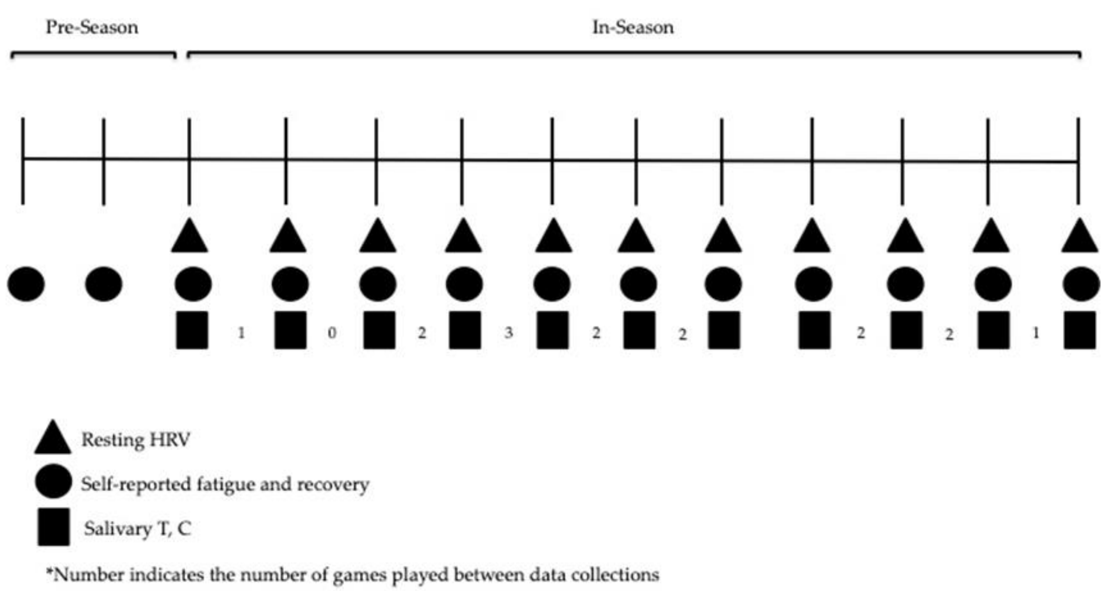

Figure 1. Timeline of data collection procedures

Heart Rate Variability: Heart rate monitors were used to record R-R intervals (First Beat Sports Monitor, Jyvaskyla, Finland) for all athletes, who were familiar with the monitors and had prior experience wearing them. Heart rate measurements were obtained at the same time of day (10:50am) prior to the scheduled practice time (11am-1pm). Heart rate was recorded for 1-min, preceded by a 1-min stabilization period (11,22) while the participants were seated comfortably and motionless and breathed naturally. Because of the skewed nature of HRV, the natural logarithm of the root mean square of successive differences (lnRMSSD) was recorded, which is an accepted marker of cardiac-parasympathetic activity, and is the preferred HRV metric for field-based monitoring (7). The R-R interval data was saved on a personal computer and synced to Firstbeat Sports using proprietary software (Firstbeat Sports) to perform an automated analysis of lnRMSSD for each one-minute segment. Measurement errors and abnormal heartbeats were eliminated by an automatic artifact detection filter process of the proprietary software.

Saliva Samples: Saliva samples were collected using the SalivaBio Oral Swab (Salimetrics, State College, PA) at the same time of the day prior to the scheduled practice time (10:50am) (12). Participants were instructed to avoid food and drinks prior to testing in order to avoid contaminating the saliva sample. Athletes sat quietly with the saliva swab under their tongues for two minutes. When prompted, athletes spit the swab into the swab storage tube, which was immediately spun in the centrifuge in preparation for pipetting. All samples were stored in a freezer at -80 degrees C until completion of the study. Batch analysis was performed for free testosterone (T), and cortisol (C) (4.2-6.3% CV) via enzyme-linked immunosorbent assay (ELISA).

Self-Reported Measures: Recovery was assessed using the Perceived Recovery Status scale (PRS), which has been previously validated as a reliable questionnaire that may correlate with athlete performance and overreaching (19,30). Fatigue was assessed using the Overall Fatigue Scale (FAT), which asks participants to rate their fatigue on a scale from 0 to 10 (31).

Statistical Analysis

SPSS version 25.0 (IBM, Armonk, NY, USA) was used for data analysis. Summary statistics for weekly lnRMSSD, T, C, and T:C are reported as mean ± standard deviation. A natural log-transformation was applied prior to analysis for any non-normally distributed variable. A repeated measures ANOVA was used to analyze changes in T, C, T:C (n=8), and lnRMSSD (n=8) over the course of the season. Due to inconsistent attendance across weeks, sample size was reduced. All data was missing at random. In order to maximize sample sizes, T, C, and T:C was assessed using weeks 3, 5, 7, 9, and 11, while lnRMSSD was assessed using weeks 1, 3, 4, 8 and 9. All assumptions (i.e. normality, spherecity, and no outliers) were tested and met. Alpha was $p < 0.05$. Bivariate Spearman correlation coefficients were used to examine relationships between lnRMSSD, T, C, T:C, recovery, and fatigue. Moderate correlations were defined as R-values of 0.41-0.70 and strong correlations were defined as R-values of 0.71-0.99.

RESULTS

Average (mean ± SD) values for lnRMSSD ranged from 3.3 ± 0.6 (week 1) to 3.9 ± 0.5 (week 12); T:C from 0.031 ± 0.022 (week 6) to 0.047 ± 0.031 (week 11); T from 0.151 ± 0.091 nmol·L^{-1} (week 9) to 0.224 ± 0.083 nmol·L^{-1} (week 11); and C from 5.51 ± 1.77 nmol·L^{-1} (week 9) to 6.81 ± 3.52 (week 4) (Table 1).

All data are presented as descriptive values. The inconsistent participation resulted in limited sample sizes across weeks and likely prevented statistically significant findings. Weekly lnRMSSD, T:C, T, and C responses are displayed in Table 2.

Table 2. Descriptive lnRMSSD, T:C, T, and C across a competitive lacrosse season.

Week	lnRMSSD	T:C	T	C
1	3.3 ± 0.6 n=12	N/A	N/A	N/A
2	3.4 ± 0.3 n=12	N/A	N/A	N/A
3	3.3 ± 0.6 n=13	0.036 ± 0.026 n=18	0.170 ± 0.049	6.14 ± 2.66
4	3.6 ± 0.4 n=14	0.033 ± 0.020 n=18	0.181 ± 0.076	6.81 ± 3.52
5	3.5 ± 0.6 n=5	0.034 ± 0.017 n=17	0.176 ± 0.076	5.95 ± 2.14
6	3.4 ± 0.4 n=9	0.031 ± 0.022 n=20	0.156 ± 0.079	5.97 ± 2.46
7	3.9 ± 0.4 n=6	0.041 ± 0.028 n=14	0.185 ± 0.099	5.52 ± 1.88
8	3.3 ± 0.7 n=13	0.033 ± 0.016 n=16	0.168 ± 0.077	5.61 ± 1.86

9	3.8 ± 0.5 n=12	0.031 ± 0.020 n=16	0.151 ± 0.091	5.51 ± 1.77
10	3.6 ± 0.5 n=5	0.035 ± 0.017 n=17	0.203 ± 0.083	6.13 ± 1.64
11	3.7 ± 0.3 n=7	0.047 ± 0.031 n=16	0.224 ± 0.083	5.77 ± 3.02
12	3.9 ± 0.5 n=7	0.044 ± 0.011 n=8	0.191 ± 0.053	4.49 ± 1.15
13	3.7 ± 0.4 n=5	0.036 ± 0.018 n=11	0.196 ± 0.072	5.84 ± 1.54

Values are mean ± SD

No significant time effect was observed in T (p=0.059), C (p=0.544), T:C (p=0.120), or lnRMSSD (p=0.062) for 8 players across the season. Though no significant time effect was observed, T increased from week 3 through week 7 (mean difference; 90% CI: 0.036; -0.048-0.120), but decreased at week 9 (-0.019; -0.058-0.20). The highest T was observed at week 11 (0.224 nmol·mL^{-1}). C increased from week 3 to week 5 (0.448; -1.38-2.28), decreased at week 7 (-0.097; -2.21-2.02), but increased from week 7 to week 9 (0.690; -1.97-3.35). C values were the highest at week 9 (5.92 nmol·L^{-1}). T:C decreased from week 3 to week 5 (-0.003; -0.033-0.026), increased at week 7 (0.007; -.038-0.024), decreased at week 9 (-0.008; -0.026-0.009), and increased to its highest value at week 11 (0.018; -0.009-0.045). lnRMSSD decreased from week 1 to week 3 (-0.095; -0.551-0.357), increased from week 3 to week 9 (0.430; -0.201-0.906). While no changes were significant, large inter-individual variability was observed, reinforcing the need for individualized monitoring.

Correlations among lnRMSSD, T, C, T:C, recovery, and fatigue are shown in Table 3. Because correlations were considered weak, further regression models were unnecessary to assess.

Table 3. Correlations and 95% CI among internal stress measures for the team.

	T	C	T:C	Recovery	Fatigue
LnRMSSD	0.265* (0.29-0.41)	-0.232* (-0.21- -0.01)	0.345** (0.12-0.56)	0.191	-0.256* (-0.29-0.13)
T	1	0.102	0.626*** (0.51-0.75)	0.041	0.171
C		1	-0.591*** (-0.72--0.47)	-0.185* (0.02-0.35)	0.017
T:C			1	0.208* (0.03-0.34)	0.201
Recovery				1	-0.672*** (-0.81- -0.59)
Fatigue					1

DISCUSSION

This is the first study to examine measures of internal stress across a competitive season (13 weeks) in NCAA DI women lacrosse athletes. The purposes were to 1) monitor resting hormonal and physiological responses across a competitive season in National Collegiate Athletic Association-Division I (NCAA-DI) women lacrosse athletes and 2) determine the relationship between measures of hormonal, physiological, and self-assessments of fatigue and recovery. Contrary to our hypotheses, the main findings of this study were that no changes in T, C, T:C, or lnRMSSD were observed throughout the season, indicating athletes did not experience maladaptation to in-season training loads. Further, weak to strong correlations existed among IL measures, demonstrating the relationship among physiological, hormonal, and psychological markers of load.

The lnRMSSD appears to follow an upward trend throughout the season. This may be suggestive of a positive physiological adaptation that occurred in response to season training. Interestingly, highest lnRMSSD was reported in week 7 (3.9 ± 0.4), which followed three competition games, the highest number of games played in one week. While we expected to observe a reduction in lnRMSSD due to fatigue from cumulative playing load, this may be indicative of a positive response from the increased training.

In previously published data (10,14,15) from collegiate women soccer athletes, the lnRMSSD displayed greater fluctuation than the lacrosse athletes in the current study (3.07 to 5.35 (15) vs. 3.3 ± 0.6 to 3.9 ± 0.4). However, in the aforementioned study with soccer athletes, data were collected over a 3-week macrocycle, thus making it difficult to compare with the 13-week sport season from the current study. Further, soccer athletes were tested during the off-season and pre-season, and thereby exposed to different training demands than the lacrosse athletes who were in-season. Frequently, lacrosse is compared to soccer due to similar high-intensity and intermittent demands of each sport (9); however, there are field location restrictions placed upon certain lacrosse positions. With soccer, these restrictions are nonexistent, which may result in a higher level of fitness when compared to lacrosse athletes. Further, the lack of consistent sample sizes across weeks reduces the power in the current study, making comparisons difficult.

While no studies have routinely assessed lnRMSSD throughout an entire season in women collegiate field athletes, lnRMSSD response was shown to be position-specific in collegiate football players during their pre-season training camp (13). While mid-skill positions demonstrated no meaningful changes across the 13 days (range: 3.87 ± 0.48 to 4.10 ± 0.46), skill positions demonstrated small-moderate progressive increases from days 3-8 (4.05 ± 0.41 to 4.37 ± 0.43), with a large peak on day 12 (4.42 ± 0.31), and linemen positions experienced a moderate reduction on day 2 (3.58 ± 0.56) and a large peak on day 12 (4.49 ± 0.36) (13). The progressive increases in skill and linemen may suggest a positive physiological adaptation, whereas the lack of improvement in mid-skill positions suggests the response to training load was not as favorable.

In the current study the T:C exhibited little change from the beginning of in-season play to its completion with the lowest peak observed at week 9 and the highest peak observed at week 11. The T:C is less commonly and conclusively studied in women athletes because women produce 5-7x less testosterone than males (3), making the response difficult to interpret. Acutely, others have observed heightened serum and salivary T and C in women volleyball, tennis, net ball, and soccer athletes following a single bout of sport competition (8,18,21,24).

Previous research with women runners (20), professional women football players (21), and soccer athletes (1), reported no change in salivary (1) and serum T (8). While runners demonstrated a lower salivary T:C post-competition (20), serum T:C alone was not a sufficient measure to assess cumulative fatigue in rowers (32). Therefore, T:C may be better used in conjunction with other load markers to clarify the stress response. While these data provide useful information in regard to an athlete's stress response to a single bout of competition, much less is understood about the athlete's response over a competitive season.

A 14-week study in women swimmers reported serum C concentrations were lower in T2 (week 3) compared with T1 (baseline) but increased in T3 (week 10) and T4 (week 14), and the T:C did not change (27). Elite women volleyball players were assessed four times (i.e. September, November, January, May) over their competitive season and T:C decreased by 30% across measures (p=0.009), before returning to baseline levels (26). Clearly more research is needed in this area from a wide variety of women's sports in order to create hormonal reference values.

There is limited research published research evaluating the relationship between self-assessment scales and objective internal stress markers in conjunction with one another. In the current study, lnRMSSD was positively correlated with fatigue, with starters exhibiting a greater association than non-starters. Flatt et al. used a 5-point Likert scale across a 2-week period in collegiate women soccer players and reported a strong correlation between average fatigue and the coefficient of variation in lnRMSSD (Flatt et al., 2016). Further, greater variation in lnRMSSD was associated with greater perceptions of fatigue in collegiate and elite men swimmers (2) and elite endurance athletes (20).

Our results show that T:C was positively related to perceived recovery. Previous research has shown that fatigue, as measured from the Profile of Mood States, exhibited moderate relationships to C (6), and strong relationships to T:C (Saw et al., 2015); however, other studies reporting this relationship in professional men soccer and rugby players showed no correlation between T, C, and T:C to fatigue (28,34). The relationship between recovery and hormones remains limited and contrasting and warrants further investigation to help practitioners determine the efficacy of self-assessment scales. While studies have assessed relationships between exercise heart rate and hormones, no studies have examined the association between resting lnRMSSD and resting hormonal secretion.

The main strength of this study is the use of routine, weekly longitudinal monitoring across an entire competitive season. Additionally, women lacrosse athletes are underrepresented in published research and this population warrants further investigation. However, limitations do exist. First, the small sample sizes and inconsistent participation across weekly assessments makes statistical analysis difficult. Hence, only descriptive information can be presented. Last, no external load measures were obtained during this period and therefore, we cannot attribute any changes in internal stress to the physical work incurred during training.

In conclusion, we sought to understand the responses of selected IL measures throughout the course of an entire competitive season in collegiate women lacrosse athletes. Further, relationships were examined among IL measures, which may prove useful for practitioners who are determining which measures to utilize with their athletes. Despite no significant time effect, a pattern was observed in that T,C, and lnRMSSD increased over the course of the season, whereas T:C tended to show more fluctuation across measurements. Large inter-individual differences were observed in markers, and thus an individualized approach to load monitoring is recommended. In addition, lnRMSSD demonstrated associations with T, C, T:C, and fatigue, indicating the suitability of these measures. However, correlations were weak and thus, further research is needed to examine these relationships across all phases of the training cycle. Routine monitoring may help strength and conditioning practitioners, athletic trainers, and sport coaches optimize training programming to reduce injury, illness, and overtraining. Reductions in lnRMSSD or T:C, or elevations in C and fatigue, during a season may suggest a subsequent need for rest in order for athletes to sufficiently recover. Understanding the relationship between IL measures may be useful to practitioners who are beginning to implement training load monitoring in their programming.

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CHAPTER 4: STUDY 2

Relationship Between External Load and Self-Reported Measures Across an NCAA Division I Men's Soccer Pre-Season

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Running Head: External load and perceived wellness

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Abstract

Monitoring the training load in soccer is a key component of the training process as it helps set an adequate balance between training and recovery. It is well known that psychological factors can affect performance. Therefore, the purpose of this study was to examine the relationship between external and internal load markers of wellness within a collegiate soccer pre-season. Collegiate men soccer athletes (n=20; mean±SD age: 20.3±0.9 yr; body mass: 77.9±6.8kg; body height: 178.87±7.18cm; body fat: 10.0±5.0%; VO2max: 65.39±7.61mL/kg/min) participated. Self-assessments of fatigue, soreness, sleep, stress, and energy were collected daily using Likert scales. In addition, mood (vigor, depression, anger, fatigue, and confusion) was assessed using the Brief Assessment of Mood. Total distance (TD), player load (PL), high-speed distance (HSD, >13 mph), high inertial movement analysis (IMA, >3.5m/s^2), and repeated high intensity efforts (RHIE) were collected in each training session using GPS/GNSS technology. At 5 minutes post-training, athletes reported their rate of perceived exertion (RPE; Borg CR-10 Scale). Multilevel models assessed the bi-directional prediction of load markers on fatigue, soreness, sleep, energy, and sRPE ($p<0.05$). Morning ratings of soreness and fatigue were predicted by the previous afternoon's practice measures of TD, PL, HSD, IMA, RHIE, and sRPE. Morning soreness and fatigue negatively predicted that day's afternoon practice TD, PL, HSD, IMA, RHIE, and sRPE. Morning ratings of negative mood were positively predicted by previous day's afternoon practice HSD. Additionally, negative morning mood states inversely predicted HSD ($p=0.011$), TD ($p=0.002$), and PL ($p<0.001$) for that day's afternoon practice. Utilizing self-assessment scales with positional monitoring technology may enhance the understanding of training responses and inform training program development.

Introduction

Performance enhancement is a primary goal of sport training, and is often accomplished through a progressive increase (overload) of mechanical and physiological stress. However, a balance between periods of overload and recovery must be achieved if adaptations are to be engendered and burnout prevented (Fry and Kraemer, 1997). In order to maintain and monitor training loads to reduce the risk of maladaptation, the physical work (external load) incurred during a training session (Bourdon, 2017; Halson, 2014) and the athletes' internal stress responses to the stimuli imposed (internal load) have been examined (Borresen, 2009; Halson, 2014). In particular, collegiate soccer is a sport that can impose a high external load on its athletes as it involves two 45-minute halves with a potential overtime period of 30 minutes (Pinasco and Carson, 2005). Approximately 20 games are played, separated by 24-72 hours, over the course of a 12-16 week competitive season (Pinasco and Carson, 2005). Therefore, collegiate soccer athletes are subjected to high training loads with minimal rest; yet, few studies have assessed measures of training load in this population.

External load has been linked to injury in professional men soccer players with increased volume and intensity reported in weeks preceding injury (Ehrmann et al., 2016;

Malone et al., 2018). However, external load does not describe the relative physiological stress imposed upon the athlete, which may represent an important stimulus for training induced adaptations (Borressen & Lambert, 2009; Halson, 2014; Viru & Viru, 2000). Internal load is particularly important in team sports, such as soccer, where individual responses to the same external load may differ (Manzi et al., 2010). Therefore, internal load may quantify individual athlete's stress responses to training stimuli and help monitor and manipulate training-recovery balance (Wrigley et al., 2012).

Several approaches have been used to quantify the internal training load, with self-perceived feelings of wellness (i.e. soreness, fatigue, energy, stress, sleep, and mood) gaining popularity not only because they are cost-effective, quick, and easy to administer in practical field-based settings, but they also have been shown to validly display athletes' perceptual sense of fatigue-related measures and mood states (Saw et al., 2006). Reductions in perceptions of wellness are strong indicators of a maladaptive training response that have been associated with burnout and poor health (Hooper et al., 1995), leading to a reduction in motivation to engage in effortful actions (Barte et al., 2017) and sport performance (Lane et al., 2011). Currently, established sport-specific psychometric questionnaires to assess athlete training status include: Recovery-Stress Questionnaire (REST-Q) (Davis, 2006), Recovery-Cue (Kellmann, 2002), Athlete Burnout Questionnaire (Raedeke et al., 2001), Daily Analysis of Life Demands for Athletes (DALDA) (Rushall, 1990), and Athlete Distress Questionnaire (Main et al., 2009). However, these tools are lengthy and therefore, impractical for daily use in team sport settings (Twist et al., 2013).

Practitioners have been encouraged to customize questionnaires as more convenient and time efficient measures of athlete wellness (Buchheit et al., 2013; Hooper, 1995). In particular, questionnaires should include measures of fatigue, soreness, stress, energy, sleep, and mood using Likert scales for a quick assessment of self-perceived recovery status (Gastin, 2013; Gallo et al., 2016). This provides immediate and valuable information in regard to the athlete's psychometric condition prior to training, which coaches may interpret and adjust subsequent sessions as necessary (Gallo et al., 2016). Further, post-session rating of perceived exertion (sRPE = rating of perceived exertion x duration of session) is another reliable and valid self-assessment measure to subjectively assess perceived load following the cessation of training. Therefore, both pre-training and post-training self-assessment tools may be incorporated in order to understand the athletes' stress response to the imposed load placed upon them.

In professional men soccer players, pre-training self-perceived feelings of fatigue, soreness, and stress were negatively correlated with training duration, total distance, and player load (Malone et al., 2018), indicating a reduction in subsequent training volume and intensity due to low recovery status. Further, a reduced wellness z-score of -1 corresponded to an 8.9% and 4.9% reduction in volume and intensity, respectively, in elite men Australian football players (Gallo et al., 2015). While the relationship between external load and perceived wellness has not been examined in collegiate level men soccer players, in collegiate men football athletes, higher wellness and energy scores were associated with greater volume in subsequent training (Govus et al., 2017), and greater volume and intensity were associated with higher post-training feelings of soreness and stress (Wellman et al., 2019).

As mentioned previously, external load is independently associated with injury risk (Ehrmann et al., 2016; Malone et al., 2018); therefore, examining the relationship between external load and self-assessment scales of perceived wellness is of interest, as such measures may be a viable addition to athlete load monitoring. Consistent load monitoring may aid in determining athletes' stress responses to a given training stimulus and enable subsequent improvements in sport performance, overall health, and injury risk or burnout. Athletes may be more susceptible to reductions in wellness during the pre-season training (Fagundes et al., 2019), as it associated with high intensity and volume (Fry and Kraemer, 1997), placing athletes at a 2-4x higher risk of injury (Carfango and Hendrix, 2014) and burnout (Fagundes et al., 2019). Yet this time period remains understudied in men collegiate soccer players. To date, no studies have examined the relationship between external load and perceived measures of wellness in this population. Therefore, the purpose of the current study was to describe the relationship and predictive value between markers of external load and wellness throughout the pre-season window in National Collegiate Athletic Association (NCAA) Division I (DI) men soccer athletes. It was hypothesized that training volume and intensity would positively predict fatigue, soreness, stress, negative mood, and sRPE, and inversely predict energy and sleep.

Methods

Subjects

NCAA DI men soccer players (n=20) participated in this study (Table 1). All athletes were under the direction of a strength and conditioning coach and were following sport-specific training regimens with neuromuscular demands particular to their sport. Further, nutritional programming was provided by the University's sports dietitian. All participants completed a medical history form and were cleared for intercollegiate athletic participation. Risks and benefits were explained to athletes and an institutionally approved consent form was signed prior to participation. The Institutional Review Board for Human Subjects has approved all procedures.

Table 1. Physical characteristics of subjects

Age (yrs)	20.3 ± 0.9
Height (cm)	178.9 ± 7.1
Body Mass (kg)	77.9 ± 6.8
Body Fat (%)	10.0 ± 5.0
Fat Free Mass (kg)	68.5 ± 5.6
VO_2 Max ($ml \cdot kg^{-1} \cdot min^{-1}$)	65.4 ± 7.6
Vertical Jump (cm)	25.6 ± 3.7
Position	
Defender	8(40)
Midfielder	7(35)
Forward	5(25)
Academic Year	
Freshman	1(5)
Sophomore	3(15)
Junior	11(55)
Senior	5(25)
Race	
White	11(55)
Black	8(40)
Hispanic	1(5)

Values are presented as mean ± SD and n(%)

Procedures

Athletes were monitored over a two-week pre-season prior to beginning the in-season phase of training. Ten training sessions and three scrimmages were played. Descriptive training volume and intensity measures over these days are outline in Table 2. Every morning prior to breakfast (~7:00am), athletes completed perceived wellness questionnaires. Daily training sessions occurred from 9-11am, 3-5pm, or 7-9pm, with two training sessions per day on several occasions. Approximately five-minutes post-training, Rate of Perceived Exertion (RPE) was collected and session RPE (sRPE) was calculated.

Table 2. Descriptive volume and intensity measures throughout pre-season

Day	TD (m)	PL (AU)	HSD (m)	IMA (#)	RHIE (#)
1	4821.4 ± 1080.2	1324.5 ± 311.3	213.2 ± 132.9	32.0 ± 18.0	17.2 ± 9.7
2	2569.5 ± 573.6	579.1 ± 119.1	102.3 ± 95.9	16.2 ± 10.1	8.4 ± 5.3
3	3146.9 ± 396.2	760.9 ± 108.1	103.8 ± 53.9	24.4 ± 9.8	12.9 ± 5.2
4-S1	6989.2 ± 1504.6	693.4 ± 169.6	174.1 ± 101.8	23.4 ± 13.2	13.8 ± 5.1
5	4976.3 ± 731.7	561.9 ± 84.5	135.4 ± 90.1	22.1 ± 7.6	14.3 ± 4.6
6	4528.2 ± 690.3	514.4 ± 77.2	39.7 ± 49.4	27.8 ± 10.6	7.7 ± 4.8
7-S2	6544.7 ± 2920.6	661.1 ± 265.8	223.1 ± 232.3	20.2 ± 13.3	12.9 ± 9.9
8	2240.6 ± 1243.1	279.4 ± 150.8	4.4 ± 6.9	14.2 ± 10.6	2.8 ± 2.5
9	4451.9 ± 1112.2	463.1 ± 123.3	81.3 ± 66.6	12.0 ± 6.7	7.8 ± 5.3
10	3931.3 ± 627.7	460.9 ± 91.9	13.6 ± 17.0	19.3 ± 9.2	7.1 ± 3.5
11-S3	6199.3 ± 3063.4	640.7 ± 267.2	131.6 ± 130.3	25.5 ± 14.3	12.5 ± 8.7
12	2872.1 ± 886.6	326.4 ± 100.7	26.3 ± 29.2	15.7 ± 7.9	5.3 ± 3.7
13	3295.5 ± 796.9	391.9 ± 94.7	27.3 ± 22.2	12.8 ± 7.1	5.1 ± 3.7

Values are mean ± SD

TD: total distance; PL: player load; HSD: high speed distance; IMA: inertial movement analysis; RHIE: repeated high intensity effors; m: meters; S1: scrimmage 1; S2: scrimmage 2; S3: scrimmage 3

External Load

External load was quantified during all field training sessions and matches using 10 Hz GPS/GNSS technology (Optimeye S5, Catapult Sports, Melbourne, Australia). This sampling rate has proven valid and reliable for intensive movements (Scott et al., 2016). Devices were worn according to manufacturer guidelines in a supportive harness positioned between the scapulae. The selected external load measures included: total distance covered (TD), player load (PL), high speed distance (HSD; >13 mph), high inertial movement analysis (IMA; >3.5 m/s^2), and repeated high intensity efforts (RHIE: <21 seconds between each effort). Following each training session and match, data were downloaded using the proprietary software (Catapult Sports Open Field). Player load is yielded from the triaxial accelerometer within the device, expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the 3 orthogonal planes and divided by 100 (Boyd et al., 2011).

Self-Reported Measures

Perceived Wellness

Participants completed a brief wellness questionnaire in which they provided subjective ratings of sleep quantity, energy (1= none; 7= full), soreness (1= no pain; 7= worst pain possible), stress (1= none; 7= worst ever), and fatigue (0= no fatigue; 5= strong fatigue; 10= maximal fatigue (Overall Fatigue Scale (OFS)) (Hooper and Mackinnon, 1995; Urhausen and Kindermann, 2002). Further, mood was reported using the Brief Assessment of Mood (BAM), a shortened validated version of the Profile of Mood States (POMS), in which athletes indicate their levels of tension, depression, anger, vigor, fatigue, and confusion on a Likert scale from 0 (not at all) to 4 (extremely) (Dean, 1990). A negative mood measure was created from the BAM (excluding the vigor item) by summing the scores for tension, fatigue, anger, depression, and confusion. This new measure was found to be reliable (r=0.716).

Session Rate of Perceived Exertion

Rate of perceived exertion (RPE) was collected using the modified Borg CR-10 scale. Athletes provided their RPE approximately five minutes post-training session in order to avoid the recency effect and ensure their perceived intensity would reflect the entire training session (Foster et al., 2001). Further, each athlete reported RPE in isolation to avoid influence from teammates. Session RPE (sRPE) was then calculated by multiplying the given RPE by the duration of the training session in minutes (Foster et al., 2001).

Statistical Analysis

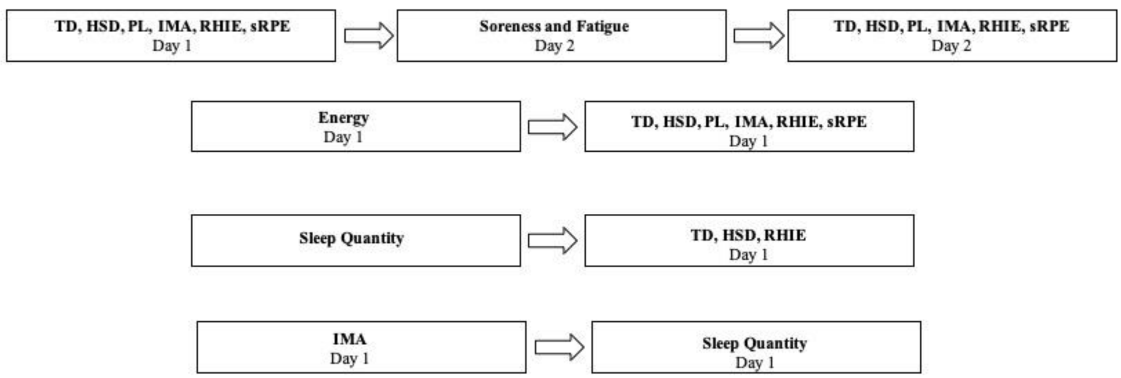
HLM 7.0 (SSI Inc., Lincolnwood, IL) was used for data analysis because data were conceptualized as hierarchically nested, or days nested within persons. These are longitudinal models, also described as growth curve models, that treats time in a flexible manner. This allows the modeling of non-linear and discontinuous change across time and accommodates unequal numbers of observations across individuals. This statistical technique has been used with similar data sets (Wunsch et al., 2017; Young et al., 2017). Hierarchical linear regression models were assessed to determine the bi-directional prediction of external load markers on fatigue, soreness, sleep, energy, stress, sRPE, and negative mood ($p<0.05$). A natural log-transformation was applied prior to analysis for any non-normally distributed variable. All assumptions (i.e. normality, homoscedasticity) were tested and met.

Results

Morning ratings of soreness and fatigue, respectively, were predicted by previous afternoon practice's TD ($\gamma20=0.000014$, $p<0.001$; $\gamma20=0.0000173$, $p=0.001$), PL ($\gamma20=0.0012$, $p<0.001$; $\gamma20=0.0014$, $p=0.001$), HSD ($\gamma20=0.003$, $p=0.002$; $\gamma20=0.004$, $p=0.003$), IMA ($\gamma20=0.0254$, $p=0.005$; $\gamma20=0.034$, $p=0.008$), RHIE ($\gamma20=0.047$, $p=0.002$; $\gamma20=0.067$, $p=0.005$), and sRPE ($\gamma20=0.001$; $p<0.001$; $\gamma20=0.001$, $p=0.005$). Morning soreness negatively predicted that day's afternoon practice TD ($\gamma10=-838.39$, $p=0.002$), PL ($\gamma10=-107.66$, $p<0.001$), HSD ($\gamma10=-20.54$, $p=0.028$), IMA ($\gamma10=-3.38$, $p=0.002$), RHIE ($\gamma10=-1.49$, $p=0.005$), and sRPE ($\gamma10=-136.37$, $p<0.001$). Morning fatigue negatively predicted afternoon practice's TD ($\gamma10=-486.067$, $p=0.002$), PL ($\gamma10=-55.3$, $p=0.001$), IMA ($\gamma10=1.566$, $p=0.006$), RHIE ($\gamma10=-1.003$, $p=0.002$), and sRPE ($\gamma10=-66.8$, $p=0.003$) (Figure 1).

Perceived energy was not affected by previous day's training load, but positively predicted TD ($\gamma10=832.7063$, $p<0.001$), PL ($\gamma10=79.19$, $p<0.001$), HSD ($\gamma10=29.37$, $p<0.001$), IMA ($\gamma10=1.5897$, $p=0.048$), RHIE ($\gamma10=1.5$, $p<0.001$), and sRPE ($\gamma10=105.138$, $p<0.001$) for same day practice. Duration of previous night's sleep positively predicted TD ($\gamma10=458.03$, $p=0.022$), HSD ($\gamma10=20.11$, $p=0.02$), and RHIE (γ10=0.909, p=0.046) for the following day's practice. Further, IMA positively predicted sleep duration later that night (γ10=0.025, p=0.002) (Figure 1). Ratings of stress had no association with any external load measure.

Figure 1. Bi-directional relationships between external and internal load measures



TD: total distance; HSD: high speed distance; PL: player load; IMA: internal movement analysis; RHIE: repeated high intensity efforts; sRPE: session rate of perceived exertion

Morning ratings of negative mood were positively predicted by previous day's afternoon practice HSD (p=0.009). Neither TD nor PL affected next day's ratings of negative mood. Additionally, negative morning mood states inversely predicted HSD (p=0.011), TD (p=0.002), and PL (p<0.001) for that day's afternoon practice. IMA and RHIE had no relationship with negative mood states.

Discussion

The aims of the current study were to assess the bi-directional relationship between subjective ratings of wellness and objective external load parameters, measured through a GNSS/GPS device. The results of this study contribute novel insight into the perceived wellness associated with pre-season competitive loads experienced by men NCAA Division I soccer players and the implementation of wellness questionnaires within a practical field-based setting. The results confirm our hypothesis that pre-training wellness was influenced by previous day's external load and also influenced external load for the upcoming training session. The most notable findings were all external load measures (total distance, player load, high speed distance, inertial movement analysis, repeated high intensity efforts) positively predicted next morning's ratings of fatigue and soreness, and those morning ratings of fatigue and soreness subsequently inversely predicted all external load measures for that afternoon's training session. Further, ratings of negative mood were highly related to total distance, high speed distance, and player load, only. Data from this study provide an increased understanding of the impact of specific external load measures on perceived wellness and support the implementation of wellness questionnaires to quantify recovery status in men NCAA Division I soccer players. These data illustrate that external load measures associated with a collegiate level soccer pre-season reflect perceptions of fatigue, soreness, energy, and sleep, and support the integration of these measures as part of a comprehensive athlete monitoring program.

Results from the current study demonstrate that fatigue and soreness were the two most predictive wellness measures of external load measures. Athletes who performed significantly higher total distance, player load, high speed distance, high inertial movement analysis, and repeated high intensity efforts reported higher fatigue and soreness the following morning, which then, in turn, led to reduced total distance, player load, high speed distance, high inertial movement analysis, and repeated high intensity efforts in that afternoon's practice. Similar findings of reduced wellness the day after sport training were demonstrated by collegiate American football players (Wellman et al., 2019). In particular, those who covered more total distance (3114 vs 3839 m), low intensity distance (2665 vs 3221 m), high intensity distance (114 vs 162 m), sprinting distance (114 vs 60 m), player load (365 vs 441 AU), and all acceleration and deceleration distances, reported higher soreness and fatigue than those who covered less volume and intensity.

Similar findings of increased perceived fatigue and soreness the following morning after competition have been demonstrated in professional men Rugby athletes (McLean et al., 2016; Twist et al., 2012), yet GPS movement variables were not thoroughly assessed in these athletes. Although fatigue and soreness after competition may be expected, the current study presents a novel investigation into which external load measures influence perceived wellness the following day, and how wellness influences that afternoon's external load during training.

In contrast to previously published data from a variety of sports, we observed no uni- or bi-directional relationship between stress and any measure of external load. Jaspers et al. (2018) reported stress as one of three most predictive wellness measures of player load, high speed distance, accelerations, and decelerations in professional men soccer players. Wellman et al. (2019) reported that lower ratings of stress 1-day post-game were associated with significantly higher player load (419.5 ± 380.2 AU), low intensity (3126.1 vs 2812.7 m) and medium intensity distance (385.7 vs 315.8 m), total distance (3729.9 vs 3314.8 m), and low intensity (1072.0 vs 951.8 m) and medium intensity deceleration distance (69.5 vs 58.8 m) during the game compared in collegiate NCAA Division I American football players. Rugby players also demonstrated this relationship during the in-season period (Hartwig et al., 2009), but prior research with the pre-season phase showed a negative effect of increased training on next morning ratings of stress in Australian football athletes (Buchheit et al., 2014). This opposite relationship during the pre-season may be due to the intensified demands associated with this training period (Hartwig et al., 2009). At the same time, stress may not be as useful a measure because it is easily influenced by other aspects of life, including family and social relationships, academic workload, and occupational responsibilities. However, other measures of wellness (i.e. fatigue, soreness, energy) are directly influenced by the actual training load. Therefore, more research is needed in collegiate men soccer athletes throughout the pre-season training phase in order to understand its role in wellness monitoring.

In the current study, previous night's sleep quantity predicted total distance, high speed distance, and repeated high intensity efforts at training, and high acceleration efforts predicted sleep quantity later that night. Studies examining the relationship between sleep and external load is limited in collegiate level athletes. However, in professional men rugby athletes, total distance (r=0.31) was associated with higher sleep quantity during the pre-season training period (Thorton et al., 2016). No relationship was seen in any external load measure in elite men soccer (Owens et al., 2014) or NCAA Division I American football players (Govus et al., 2017; Wellman et al., 2019).

In addition, our results indicated morning ratings of negative mood were positively predicted by previous day's afternoon practice high speed distance. Neither total distance nor player load affected next day's ratings of negative mood. Also, negative morning mood states inversely predicted high speed distance, total distance, and player load for that day's afternoon practice. Inertial movement analysis and repeated high intensity efforts had no relationship with negative mood states. This relationship of heightened training leading to poor mood was observed in elite kayakers (Kentta et al., 2006) and collegiate swimmers (Raglin et al., 1991), of which mood was measured using the Profile of Mood Stats (POMS). However, no relationship between mood and external load was seen in collegiate football (Wellman et al., 2019) and elite Australian football players (Govus et al., 2017). In these two studies, mood was assessed using a Likert scale rather than a brief questionnaire, perhaps leading to these contrasting findings.

It is speculated that players with low perceived wellness incorporated an altered movement strategy within training sessions with an element of self-pacing that resulted in reduced volume and intensity metrics (Malone et al., 2018). This has important consequences for practitioners as reduced wellbeing may inhibit the ability of players to attain high intensity movements, which may result in the under-preparation of players that may increase player's susceptibility to injury (Malone et al., 2017).

Findings from the current study provide novel insight into the relationship between EL and self-assessment scales for monitoring athlete training, yet limitations cannot go unmentioned. For example, no documentation of the coaches' intentions for each day's practice was taken. Therefore, it is reasonable to believe that some form of purposeful undulating periodization led to intentional low volume or intensity training sessions following high volume or intensity sessions. This would have allowed short periods of recovery inducing increased mood states the following day which athletes would proceed to perform at higher volumes or intensities. Regardless, the questionnaires may still be a valuable tool to assist in solidifying the coaches' intentions of whether the prior training session was of appropriate intensity to make judgments on the same day's training.

In conclusion, the results of this study provide novel insight into the physical and psychological responses associated with an NCAA Division I soccer pre-season. External load does indeed predict perceived wellness and perceived wellness further predicts external load output during training. Significant reductions in training volume and intensity were reported in athletes with less favorable perceived wellness, and large increases in volume and intensity led to less favorable perceived wellness. The use of a customized wellness questionnaire may provide sport and performance coaches with an improved understanding of the individual response to practice and competition, and contribute to the design of training and recovery protocols to enhance subsequent performance. The ease of administration and cost-effectiveness associated with individual athlete monitoring through wellness questionnaires, permits implementation these strategies throughout the season.

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CHAPTER 5: STUDY 3

Relationship between daily external and internal load measures during pre-season training in collegiate men soccer players

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Abstract

Monitoring internal load in conjunction with external load provides information in regard to athlete training stress and adaptation. However, the relationship between a variety of these markers across a competitive window remains inconclusive. Therefore, the purpose was to examine the relationship between external and internal load (physiological, hormonal, self-assessment scales) markers within a collegiate soccer pre-season. Collegiate men soccer athletes (n=20; mean±SD age: 20.3±0.9 yr; body mass: 77.9±6.8kg; body height: 178.87±7.18cm; body fat: 10.0±5.0%; VO2max: 65.39±7.61mL/kg/min) participated. Ultra-short natural logarithm of the root mean square of successive differences (lnRMSSD), salivary testosterone, cortisol, the testosterone:cortisol ratio, and self-assessment wellness scales were collected daily for 13 days. Total distance (TD), player load (PL), high-speed distance (HSD, >13 mph), high inertial movement analysis (IMA, >3.5m/s^2), and repeated high intensity efforts (RHIE) were collected in each training session using GPS/GNSS technology. At 5 minutes post-training, athletes reported their rate of perceived exertion (RPE; Borg CR-10 Scale). Paired t-tests were used to determine changes in external load, physiological, hormonal, and subjective self-assessment measures of internal load. Bi-directional prediction of external load markers and self-assessment measures on physiological and hormonal markers of internal load were assessed via hierarchical linear regression models. External load measures, cortisol, energy, sleep, and RPE decreased from week 1 to week 2 ($p<0.01$), while testosterone, testosterone:cortisol ratio, anger, depression, and vigor increased ($p<0.01$). Unidirectional predictions occurred between measures of external and internal load. Despite the reduction in hormonal stress and external load across weeks, negative perceptions of fatigue increased. This may suggest that patterns of fatigue have different timelines and load may have a more delayed, chronic effect on feelings whereas hormonal changes may be more immediate and sensitive to change. Therefore, practitioners may wish to use a variety of external and internal load measures in order to understand athletes' stress responses to training and to optimize sport performance and health.

Introduction

Performance enhancement, a primary goal of training for sport, is often accomplished through manipulation of physical training load (Manzi et al., 2010), such as variations in training volume and intensity (Halson, 2014; Manzi et al., 2010; Mujika et al., 2004). An athlete's physical work during a training session (i.e. total distances covered, overall movement performed, high speed running, accelerations, and sprint efforts) is referred to as external load (Bourdon, 2017; Brink et al., 2010; Halson, 2014). Previous evaluation of external load has assessed its relationship to injury status (Bowen et al., 2017; Malone et al., 2018), as well as examined performances by sport-position (Vigh-Larson et al., 2018; Waldon et al., 2011), starting status (Anderson et al., 2016), and game halves (Barros et al., 2016; Suarez-Arrones et al., 2016). However, external load does not describe the relative physiological stress imposed upon the athlete (i.e. internal load), which may represent an important stimulus for training induced adaptations (Borressen & Lambert, 2009; Halson, 2014; Viru & Viru, 2000). The internal load is particularly important in team sports, such as soccer, where individual responses to the same external load may differ (Manzi et al., 2010). Therefore, internal load may quantify an individual athlete's stress responses to training stimuli and help to monitor and manipulate training-recovery balance (Wrigley et al., 2012).

Several approaches have been used to quantify the internal training load across a range of sports, including physiological (e.g., heart rate variability), hormonal, (e.g., testoterone:cortisol ratio) and subjective self-assessment measures of wellness (e.g., fatigue, energy, soreness, stress, sleep). Resting heart rate variability (HRV) is an objective measure of cardiac-autonomic function and is reflective of an individual's physiological adaptation to training programs (Buchheit et al., 2012; Esco and Flatt, 2014; Flatt et al., 2016). An athlete's HRV has been shown to reflect internal training load, typically characterized by a suppression of parasympathetic indices, with the return of HRV to baseline mirroring recovery (Flatt et al., 2016). Chronically reduced HRV has been associated with fatigue and overtraining (Le Meur et al., 2013; Plews et al., 2012); therefore, monitoring HRV responses throughout a period of training has proven useful for monitoring the stress response in athletes.

The testosterone (T) to cortisol (C) ratio (T:C) reflects the anabolic-catabolic hormonal balance in response to training (Adlercreutz et al., 1986). Intense frequent exercise leads to increased cortisol and reduced testosterone, suggesting a negative stress adaptation. It is useful to monitor T:C during an athletic season or competitive period as it is expected to decline in response to intensified training (Urhausen et al., 1987; Vervoorn et al., 1992). Although the T:C is a physiological representation of the internal stress response, it may be costly and impractical to collect blood or saliva samples regularly.

Decrements in wellness are strong indicators of a maladaptive training response that have been associated with acute fatigue or chronic overreaching and overtraining, particularly increased soreness, fatigue, stress, depression, and anger, and reduced sleep and energy levels across a variety of athletes (Hooper et al., 1995 Malone et al., 2018). Although internal load markers may be acutely altered by exercise, little is known about the cumulative effects of training over a competitive period. Further, the strong relationship between external load and self-assessment scales has been investigated (Govus et al., 2018; Malone et al., 2018 Wellman et al., 2019), but it is unknown how the self-assessment scales relate to physiological internal load markers such as HRV and T:C. Consistent load monitoring may help to enhance sport performance, improve overall health, and reduce the risk of injury and overtraining, particularly in the pre-season when training intensity and volume are high (Fry and Kraemer, 1997), thereby placing athletes at a 2-4x higher risk of injury (Carfango and Hendrix, 2014). To date, information on athlete load monitoring is limited in collegiate men soccer athletes. Therefore, the purpose of this comprehensive study was to describe the relationship between measures of external load and internal load throughout a pre-season in collegiate men soccer athletes. A second purpose was to describe and examine changes in these measures of load throughout this period of competitive play.

Methods

Subjects

National Collegiate Athletic Association Division I (NCAA DI) men soccer players (n=20) participated in this study (Table 1). All athletes were under the direction of a certified strength and conditioning coach (NSCA-CSCS) and were following sport-specific training regimens with neuromuscular demands particular to their sport. Further, nutritional programming was provided by the University's registered sports dietitian. All athletes completed a medical history form and were cleared for intercollegiate athletic participation. Risks and benefits were explained to athletes and an institutionally approved consent form was signed prior to participation. The Institutional Review Board for Human Subjects approved all procedures.

Table 1. Physical characteristics of subjects (n=20)

Age (yrs)	20.3 ± 0.9
Height (cm)	178.9 ± 7.1
Body Mass (kg)	77.9 ± 6.8
Body Fat (%)	10.0 ± 5.0
Fat Free Mass (kg)	68.5 ± 5.6
VO2 Max (ml·kg^{-1}·min^{-1})	65.4 ± 7.6
Vertical Jump (cm)	25.6 ± 3.7

Values are mean ± SD

Procedures

Athletes were monitored over a two-week pre-season prior to beginning the fall academic semester, which consisted of ten training sessions and three scrimmages. Every morning prior to breakfast (~7:00am), athletes completed self-assessment wellness questionnaires. Daily training sessions took place in one of three blocks: 9-11am, 3-5 pm, or 7-9 pm. On seven of 13 days, two training sessions were held. Session Rate of Perceived exertion (sRPE) was collected and calculated five minutes following the cessation of training.

External Load

External load was measured for field training sessions and matches using 10 Hz GPS/GNSS technology (Optimeye S5, Catapult Sports, Melbourne, Australia). The predetermined sampling rate has good validity and reliability for high intensive movement demands (Scott et al., 2016). The external load measures included: total distance covered (TD), player load (PL), high speed distance (HSD; >5.8 m/s), high inertial movement analysis (IMA; >3.5 m/s^2), and repeated high intensity efforts (RHIE: <21 seconds between each effort). Following each training session and scrimmage, data were downloaded using the proprietary software (Catapult Sports Open Field).

Internal Load

Physiological Measures

Heart rate monitors were used to record R-R intervals (Polar H7) and all athletes were familiar with the monitors and had prior experience wearing them. In accordance with company provided guidelines, the electrode belt was dampened and placed tightly but comfortably just below the chest muscles. Heart rate measurements were obtained at the same time of day (7:00am) prior to breakfast (11am-1pm). Heart rate was recorded for 1-

min, preceded by a 1-min stabilization period (Esco and Flatt, 2014; Nakamura et al., 2015) while athletes remained seated comfortably, motionless, and breathed naturally. The natural logarithm of the root mean square of successive differences (lnRMSSD) was recorded, which is an accepted marker of cardiac-parasympathetic activity, and is the preferred HRV metric for field-based monitoring (Buchheit et al., 2012). The R-R interval data was saved on a personal computer and synced using proprietary software to perform an automated analysis of lnRMSSD for each one-minute segment. Measurement errors and abnormal heartbeats were eliminated by an automatic artifact detection filter process of the proprietary software.

Hormonal Measures

Saliva samples were collected using the SalivaBio Oral Swab (Salimetrics, State College, PA) each day prior to breakfast (7:00am) (Filaire et al., 2001). Athletes were instructed to avoid food and drinks prior to testing in order to avoid contaminating the saliva sample. To ensure a clean and adequate volume of sample, water was provided prior to collection. Athletes sat quietly with the saliva swab under their tongues for two minutes. When prompted, athletes spit the swab into the swab storage tube, which was immediately spun in the centrifuge in preparation for pipetting. All samples were stored in a freezer at -80 degrees C until completion of the study. Batch analysis was performed for testosterone and cortisol via enzyme-linked immunosorbent assay (ELISA) (Monobind, Lake Forest, CA, USA). Intra-assay coefficient of variation for testosterone and cortisol was 3.9% and 4.2%, respectively.

Self-Assessment Measures

Perceived Wellness and Mood

Athletes completed a brief wellness questionnaire by providing subjective ratings of sleep quantity, energy (1= none; 7= full), soreness (1= no pain; 7= worst pain possible), stress (1= none; 7= worst ever), and fatigue (0= no fatigue; 5= strong fatigue; 10= maximal fatigue (Overall Fatigue Scale (OFS)) (Hooper and Mackinnon, 1995; Moalla et al., 2016; Urhausen and Kindermann, 2002). Further, mood was reported using the Brief Assessment of Mood (BAM), a shortened validated version of the Profile of Mood States, which required athletes to indicate their levels of tension, depression, anger, vigor, fatigue, and confusion on a Likert scale from 0 (not at all) to 4 (extremely) (Dean, 1990).

Session Rate of Perceived Exertion

Rate of perceived exertion (RPE) was collected using the modified Borg CR-10 scale. Athletes provided their RPE approximately five minutes post-training session in order to avoid the recency effect and to ensure their perceived intensity would reflect the entire training session (Foster et al., 2001). Further, each athlete reported RPE in isolation to avoid influence from teammates. Session RPE (sRPE) was then calculated by multiplying the given RPE by the duration of the training session in minutes (Foster et al., 2001).

Statistical Analysis

SPSS version 25.0 (IBM, Armonk, NY, USA) was used for summary statistics. A natural log-transformation was applied prior to analysis for any non-normally distributed variable. Daily practice measures were grouped by week (week 1: sessions 1-6 week 2: 7-13) and paired t-tests were used to determine changes in external load (total distance, player load, high speed distance, high inertial movement analysis, repeated high intensity efforts), physiological (HRV, % max HR), hormonal (T, C, T:C), and subjective self-assessment (fatigue, soreness, energy, stress, sleep, mood) measures of internal load. Because of multicollinearity between TD and PL, significance was reduced to $p<0.025$. All other assumptions were tested and met (i.e. independent observations, normality, no outliers). Further, HLM 7.0 (SSI Inc., Lincolnwood, IL) was used for data analysis because data were conceptualized as hierarchically nested, or days nested within persons. These are longitudinal models, also described as growth curve models, that treats time in a flexible manner. This allows the modeling of non-linear and discontinuous change across time and accommodates unequal numbers of observations across individuals. This statistical technique has been used with similar data sets (Wunsch et al., 2017; Young et al., 2017). Hierarchical linear regression models assessed the bi-directional prediction of external load markers and self-assessment measures on physiological and hormonal markers of IL.

Results

The 13-day pre-season consisted of ten training sessions and three scrimmages. Total distance ranged from 2240.6 ± 1243.1 m to 6989.2 ± 1504.6; player load ranged from 279.4 ± 150.8 to 1324.5 ± 311.3 AU; high speed distance ranged from 4.4 ± 6.9 to 223.1 ± 232.3 m; high inertial movement analysis ranged from 12.0 ± 6.7 to 32.0 ± 18.0 efforts; and repeated high intensity efforts ranged from 2.8 ± 2.5 to 17.2 ± 9.7 efforts.

Daily T, C, and T:C are included in Figure 1 and Figure 2.

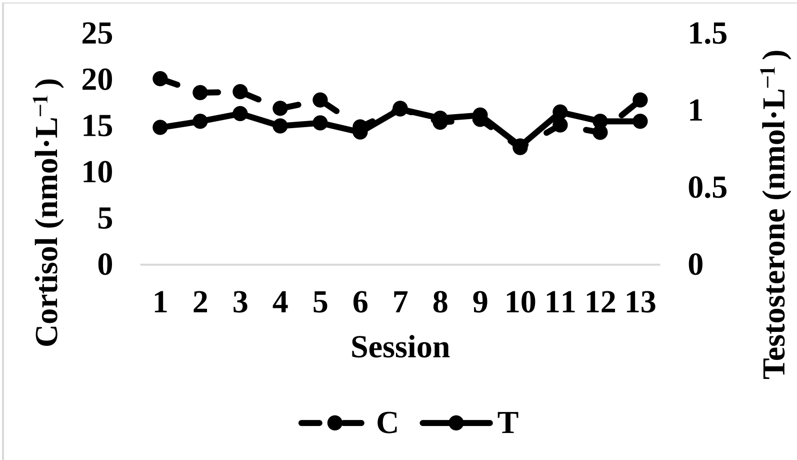

Figure 1. Daily testosterone and cortisol values across a two-week pre-season

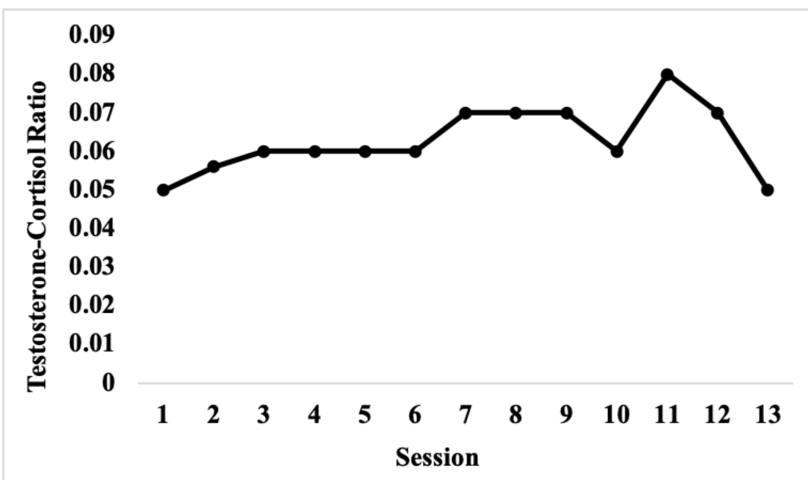

Figure 2. Daily testosterone-cortisol values across a two-week pre-season

External and internal load measures significantly changed from week 1 to week 2 (Table 1).

Table 1. Changes in external and internal load measures from week 1 to week 2

	Week 1	**Week 2**	**p-value**
Volume (external load)			
TD (m)	6246.5 ± 1045.9	4429.9 ± 811.9	<0.001
PL (AU)	726.6 ± 124.0	527.5 ± 333.8	0.002
Intensity (external load)			
HSD (m)	124.3 ± 68.8	71.6 ± 56.6	<0.001
RHIE (#)	12.2 ± 4.5	7.4 ± 3.3	<0.001
IMA (#)	24.5 ± 8.4	16.7 ± 6.2	<0.001
Physiological (internal load)			
HRV (lnRMSSD)	4.26 ± 0.25	4.23 ± 0.20	0.585
% Max HR	72. 56 ± 2.76	70.97 ± 4.03	0.027
Hormonal (internal load)			
T ($nmol \cdot L^{-1}$)	0.903 ± 0.223	0.959 ± 0.205	0.008
C ($nmol \cdot L^{-1}$)	16.60 ± 5.54	14.53 ± 3.72	0.001
T:C	0.055 ± 0.017	0.070 ± 0.022	<0.001
Self-Assessments (internal load)			
Soreness (AU)	2.7 ± 0.9	2.6 ± 0.9	0.389
Fatigue (AU)	2.7 ± 1.2	2.5 ± 1.3	0.259
Energy (AU)	4.5 ± 0.9	3.6 ± 0.9	<0.001
Stress (AU)	2.1 ± 0.7	2.0 ± 0.8	0.450
Sleep (AU)	6.7 ± 0.6	6.2 ± 0.8	0.002
Anger (AU)	0.18 ± 0.29	0.42 ± 0.43	0.016
Depression (AU)	0.10 ± 0.23	0.52 ± 0.6	0.001
Vigor (AU)	0.14 ± 0.27	0.36 ± 0.45	0.006
sRPE (AU)	752.4 ± 133.8	452.0 ± 105.1	<0.01

Values are mean ± SD

m: meters; AU: arbitrary units

TD: total distance; PL: player load; HSD: high speed distance; IMA: inertial movement analysis; RHIE: repeated high intensity efforts; HRV: heart rate variability; T: testosterone; C: cortisol; T:C: testosterone-cortisol ratio; sRPE: session rate of perceived exertion

Morning C predicted mood ($\gamma20=-0.654702$, $t=-3.599$, $p=0.002$), energy ($\gamma20=0.876219$, $t=2.982$, $p=0.002$), total distance ($\gamma20= 207.008130$; $t=3.747$; $p=0.002$), player load ($\gamma20=24.013$, $t=3.419$, $p=0.004$), high speed distance ($\gamma20=6.850317$, $t=2.939$, $p=0.01$), high inertial movement analysis ($\gamma20=0.450479$, $t=2.459$, $p=0.026$), RHIE ($\gamma20=0.525$, $t=3.228$, $p=0.005$), and sRPE ($\gamma20=34.96$, $t=3.60$, $p=0.002$) (Figure 2). Morning T:C also predicted mood ($\gamma20=0.002359$, $t=3.202$, $p=0.006$), energy ($\gamma20=-0.004638$, $t=-3.187$, $p=0.006$), total distance (-534.49; -4.150; $p<0.001$), player load ($\gamma20=-6070.622$, $t=-4.30$, $p<0.001$), high speed distance ($\gamma20$ -1819.101779, $t=3.210$, $p=0.005$), high inertial movement analysis ($\gamma20=-164.935$, $t=-3.663$, $p=0.002$), RHIE ($\gamma20=-112.0$, $t=-3.630$, $p=0.002$), and sRPE ($\gamma20=-8235.15$, $t=-4.229$, $p<0.001$) (Figure 2). HRV predicted sRPE ($\gamma20=--404.25$, $t=-2.385$, $p=0.031$) and soreness predicted %max heart rate ($\gamma20=-0.0000232$, $t=-2.590$, $p=0.021$). In addition, previous day's high inertial movement analysis was the only external load measure to predict C ($\gamma20= 0.074741$; $t=1.98$; $p=0.05$) (Figure 3). No relationship was observed between any other internal load and external load measure.

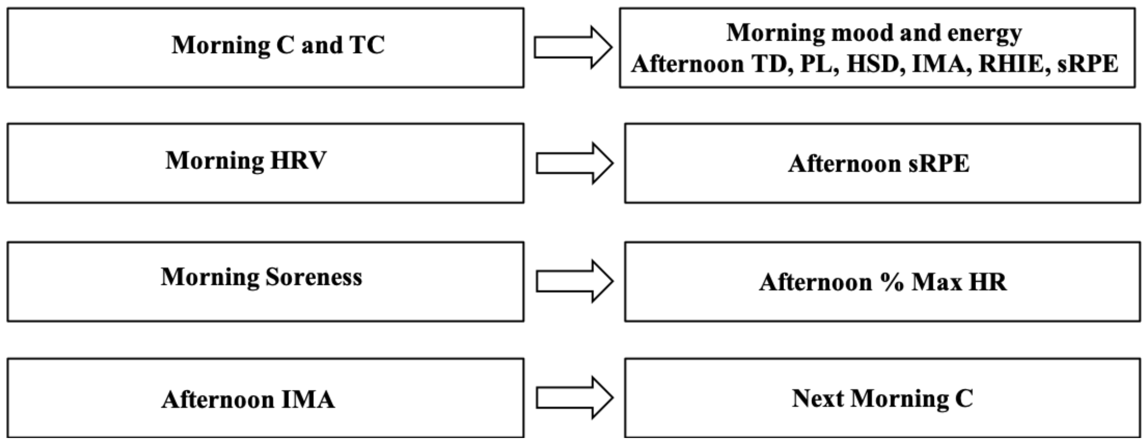

Figure 3. Bi-directional relationships between external and internal load markers
C: cortisol; TC: testosterone-cortisol ratio; TD: total distance; PL: player load; HSD: high speed distance; IMA: inertial movement analysis; RHIE: repeated high intensity efforts; sRPE: session rate of perceived exertion; HRV: heart rate variability

Discussion

This is the first study in which the relationship among measures of external and internal load was examined across a 13-day pre-season period in NCAA DI men soccer athletes. The purposes were to 1) monitor daily resting internal (physiological, hormonal, and perceived wellness) and external load, 2) assess weekly changes in external and internal load, and 3) determine the bi-directional predictability between various markers of external and internal load. The results provide insight into the demands associated with pre-season competitive loads experienced by NCAA DI men soccer athletes. A main finding was that athletes are subjected to significantly higher external training loads in the first week of pre-season; however, in contrast to our hypothesis, not all measures of training load were associated with one another.

Previous research in elite men soccer athletes (Anderson et al., 2016; Dalen et al., 2016; Rampinini et al., 2011; Varley et al., 2014) reported the total distance covered during matches ranged from 10,776-12,190 m, including: 1196 – 1309m, high intensity running (>19km-hr); 668 ± 28 m, high speed distance (19.8 to 25.2 km·h⁻1); and 143 ± 10 m, sprinting (≥25.2 $km \cdot h^{-1}$) (Rampinini et al., 2011). Further, game IMAs (>2m/s^2) and accelerations (>2.78 m/s^2) were reported as 76 ± 22 efforts (Dalen et al., 2016) and 65 ± 21 efforts, respectively (Varley et al., 2014). When compared to matches, training sessions averaged 5223 ± 406 m for total distance, and high speed distance ranged from 8 – 104 m (Anderson et al., 2016). Upon comparison, our external load measures were lower; however, it should be noted that previous research examined in-season periods. During our pre-season period of data collection, the sport coach experimented with the starting lineup and playing time, thus substitutions were common and players received comparable playing time. This may have contributed to lower external load values during our pre-season scrimmages compared to values reported for in-season matches with professional teams. Also, in an attempt to identify bouts of very high intensity playing efforts, we selected a higher IMA cutoff value (i.e., 3.5 m/s^2) than the moderate intensity value (2.0-2.78 m/s^2) typically used in previous studies (Dalen et al., 2016, Varley et al., 2014).

Acute changes in T, C, and the T:C occur immediately post-competition with studies reporting 1.5-2.5x higher salivary C and a 62% T:C reduction (Elloumi et al., 2003; Lac et al., 2000), indicating a substantial acute catabolic effect. Yet, limited information exists on athletes' responses over a competitive season. Previous results in men and women collegiate soccer athletes demonstrated C to be elevated from pre-season throughout the season (Kraemer et al., 2004; Walker et al., 2019), T to be increased by the end of the season in both starters and non-starters, and T:C to be increased by the end of season in non-starters (Kraemer et al., 2004). These findings indicate that players entering the season with reduced T and elevated C may not be able to return to resting concentrations, thus in-season performance may be compromised as a result of pre-season training. The pre-season window, therefore, is important because training loads are typically 2-4x greater than in-season loads (Carfango et al. 2014) thus injury risk may be higher with unrecovered athletes.

The decrease in C, and increases in T and T:C from week 1 to week 2 in the current study are in line with the significant reductions in training volume (total distance, player load) and intensity (high speed distance, high inertial movement analysis, and repeated high intensity efforts) that was observed across the pre-season period. Even though soccer athletes engaged in lower volume and intensity during week 2, perceived energy and sleep quantity were reduced, while anger and depression increased. These adverse changes to athlete wellness may have resulted from the cumulative effect of the high loads experienced in week 1. Despite changes in hormonal and wellness stressors, lnRMSSD remained unaltered. Although athletes in the current study demonstrated increased anabolism and decreased catabolism, a negative impact on mood states was exhibited prior to entering in-season play. Thus, the physiological, hormonal, and perceived changes appear to rely upon the alterations in training load.

Results from the current study demonstrated morning C positively predicted afternoon external load measures (total distance, player load, high speed distance, high inertial movement analysis, and repeated high intensity efforts), and sRPE. Further, T:C positively predicted mood, while negatively predicting perceived energy, afternoon external load measures (total distance, player load, high speed distance, high inertial movement analysis, and repeated high intensity efforts), and sRPE. In contrast to our results, sprint efforts in professional men soccer athletes (Thorpe and Sunderland, 2012) and total distance in rugby athletes (McLellan et al., 2010) were not associated with pre- and post-match salivary T or C. However, in line with the current study, others found a reduction in sRPE to be associated with a reduction in T:C in professional men soccer players (Rowell et al., 2018). While it was expected that C would negatively predict external load and external load would subsequently positively predict next day C, the opposite relationship we observed may be a result of athlete anxiety over the anticipated high training loads of that afternoon's practice. Despite having elevated C, athletes trained at high loads, and it is unknown how these elevations may have chronically impacted their performance.

In the current study, morning HRV was not associated with external load measures during afternoon practice or scrimmage. In agreement, others report no daily relationships; however, large correlations existed between lnRMSSD and weekly player load in NCAA DI football players (Flatt et al., 2018). In elite men soccer players, the relationship between lnRMSSD and total distance, acceleration, and high speed distance (Bryna et al., 2019; Thorpe et al., 2015) were trivial. Yet, using HRV to monitor training responses is challenging as it is influenced by factors independent of work performed, including body mass, fitness, exercise intensity, weather, and hydration (Flatt et al., 2018). Thus, the lack of associations between HRV and performance may be partially attributed to the hot and humid pre-season climate (temperature average: 32.2° C), which may impact hydration levels and subsequently suppress InRMSSD.

The lack of association between lnRMSSD and perceived fatigue contrasts various studies in support of this relationship (Flatt et al., 2016; Flatt et al. 2018; Rabbani et al., 2018). Flatt et al. reported lnRMSSD was higher with better quality sleep and mood states, combined with lower fatigue and stress in men collegiate swimmers, while no relationship existed between lnRMSSD and soreness (Flatt et al., 2018). The lack of association between perceived muscle soreness and HRV suggests that athletes may experience muscle soreness despite lnRMSSD being at or above baseline, highlighting a limitation of HRV as a complete marker of recovery status.

We hypothesized that stress and mood would be inversely related to HRV, as the sympatho-adrenal medullary and hypothalamic-pituitary-adrenocortical axes mediate the physiological response to stress by modulating parasympathetic and sympathetic activity. Although current results are in contrast with our hypothesis, they are in support of previous findings of no association between HRV and tension, depression, anger, confusion, and vigor among a variety of men and women athletes (Saw et al., 2016). However, others reported lnRMSSD was positively associated with perceived fatigue in endurance athletes throughout three weeks of overload training (Le Meur et al. 2013). These contrasting results in the literature may be due to varying methodological approaches to obtain HRV (i.e. 1-minute vs. 5-minute recordings and stabilization periods; frequency vs time domains). Further, physiological responses may be more sensitive and easily altered than perceived feelings. The lack of relationship between hormonal and physiological measures, in the current study, supports prior findings (Solana et al., 2018). However, making further comparisons is difficult as limited information exists, despite the hypothesis that elevated C, and reduced T and T:C would be related to a depressed lnRMSSD.

Cortisol may influence behavior changes (Chennaoui et al., 2016), with high cortisol levels observed following peak stressors (Smyth et al., 1998). In the current study, morning C and T:C significantly predicted mood and energy, whereas no relationship was observed with soreness, fatigue, stress, or sleep. Previous research in women athletes of various sports found cortisol to positively relate to fatigue, depression, confusion, and anxiety (Chennaoui et al., 2016), while negatively relating to tension-anxiety mood (Di Corrado et al., 2014). Moreover, following training in women, C has shown inverse relations to positive mood (Smyth et al., 1998). In contrast, no relationship between T, C, and T:C and mood (POMS and BAM) and soreness, fatigue, sleep, and stress, were apparent in other men and women professional athletes (Broodryk et al., 2017; Buchheit et al., 2013; Filaire et al., 2002; West et al., 2014). However, many of these studies assessed acute responses to training and matches; therefore, the chronic relationship among these variables warrants further investigation.

In conclusion, the current results provide insight on external and internal stress responses associated with an NCAA Division I soccer pre-season training period. While there were no changes in lnRMSSD, fatigue, soreness, or stress from week 1 to week 2, TD, PL, HSD, IMA, RHIE, C, energy, and sleep decreased, and T, T:C, depression, anger, and vigor increased. Interestingly, despite the reduction in hormonal stress and external load across weeks, negative perceptions in regard to fatigue increased (reduced energy; higher depression and anger). This may suggest that patterns of fatigue have different timelines and load may have a more delayed, chronic effect on feelings whereas hormonal changes may be more immediate and sensitive to change. Therefore, practitioners may wish to use a variety of external and internal load measures in order to understand athletes' stress responses to training and to optimize sport performance and health.

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CHAPTER 6: GENERAL SUMMARY AND CONCLUSIONS

The overall purpose of this dissertation was to examine markers of external and internal load, as well as their relationships, across a competitive window in men and women collegiate athletes. Previous researchers have investigated the effects of sport training on single markers of internal load, but the majority of research has focused on acute responses and few markers of load in professional level athletes. Therefore, the studies in this dissertation were designed specifically to address the lack of research focusing on longitudinal responses, the relationships among a variety of load markers, and collegiate level athletes.

Specifically, Study 1 (Chapter 3) provided descriptive information in regard to a variety of load markers, including salivary testosterone, cortisol, and the testosterone:cortisol ratio, as well resting heart rate variability, throughout a competitive season in women lacrosse players. While there was no statistically significant change in any internal load marker across the season, low to moderate correlations existed between physiological, hormonal, and self-perceptions of fatigue. The lack of change was not expected, however the inconsistent sample sizes made statistical analysis difficult to power. On the other hand, the relationships between physiological and hormonal measures were expected, indicating resting heart rate variability may be a viable, non-invasive marker when salivary hormonal collection is not plausible. Nevertheless, it is challenging to interpret internal load responses without external load.

Study 2 (Chapter 4) showed the bi-directional relationship between external load and self-assessment wellness scales, such that previous day's external load positively predicted morning rating of fatigue and soreness, which in turn inversely predicted that afternoon's external load. Because external load has shown to be independently related to injury risk, and this study supports the strong relationship between external load and self-assessment wellness scales, such measures may be a viable addition to athlete load monitoring. The use of a customized wellness questionnaire may provide sport and performance coaches with an improved understanding of the individual response to practice and competition, and contribute to the design of training and recovery protocols to enhance subsequent performance. The ease of administration and cost-effectiveness associated with individual athlete monitoring through wellness questionnaires, permits implementation of these strategies throughout the season.

Study 3 (Chapter 5) was designed to comprehensively examine a variety of internal load markers (physiological, hormonal, self-assessment scales) and its relationship to external load. Because there is no single identifier marker of overtraining and maladaption, it is difficult for practitioners to determine the most effective and practical markers to monitor in their programs. No studies have provided such a comprehensive analysis of these relationships. Further, changes in load markers across the pre-season were investigated. The results of this study showed that morning cortisol positively predicted all external load measures and energy, while it negatively predicted mood. In turn, high inertial movement analysis efforts significantly predicted cortisol the following morning. Heart rate variability negatively predicted session RPE post-training, and soreness negatively predicted % max heart rate during training. Therefore, only few measures of training load were successful in predicting one another. In addition, all external load measures, cortisol, energy, and sleep decreased from week 1 to week 2, while testosterone, testosterone:cortisol, anger, depression, and vigor increased. This may suggest that patterns of fatigue have different timelines and load may have a more delayed, chronic effect on feelings whereas hormonal changes may be more immediate and sensitive to change. Therefore, practitioners may wish to use a variety of external and internal load measures in order to understand athletes' stress responses to training and to optimize sport performance and health.

Practical Implications

Collectively, these studies show that a variety of external and internal load markers should be utilized when assessing athletes' training status. Practitioners should be encouraged to incorporate a variety of load monitoring strategies as it is clear there is no single best marker to determine the balance between overload and recovery. When incorporating various load markers into a team's routine, it is important to first assess a baseline for each athlete. By doing so, practitioners can subsequently monitor deviation from baseline to ensure sufficient recovery and enhanced adaptation while reducing the risk of injury, NFOR, and OTS. This strategy permits the individualization of athlete load monitoring.

Further, practitioners can utilize load monitoring to adapt training programs to individual athlete needs. For example, if several athletes show altered physiological (i.e. depressed lnRMSSD) and hormonal (reduced T, T:C, and elevated C) balance, coaches should opt to forego a high intensity training session and replace it with a recovery session to reduce the risk of overtraining. In addition to examining internal stress, practitioners should utilize EL values to ensure training sessions are sufficient in preparing athletes for the physical demands of matches. If athletes are not exposed to match loads, they are at higher risk of injury due to under-preparation. At the same time, too high of loads may lead to altered internal stress, placing athletes at further risk of injury and reduced health. Therefore, EL must be examined in conjunction with a variety of IL measures to understand athlete adaptation to training.

This dissertation sheds light on how load markers change and are related to one another throughout competitive periods of the season. Because this is one of the first studies to comprehensively examine the relationship of several load markers across a competitive window, further investigation into these relationships is warranted. Additionally, future studies should investigate the full season in addition to the pre-season period. Previous research has indicated that athletes entering the in-season fatigued and injured from pre-season never fully recover and performance continues to decline through season play. Therefore, understanding the demands of pre-season and the transition into in-season will be a critical component in future research.

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BIOGRAPHY

Jen completed her BS in Kinesiology from the University of Maryland. While an undergraduate, she began personal training and developed a passion for fitness and nutrition. She went on to complete her MS in Health Promotion and Nutrition from American University, where she focused her studies on Sports Nutrition. Jen’s work throughout her doctorate program has been centered around improving athlete health and sport performance.