Athlete Monitoring in American Collegiate Football

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Academic Abstract

American football is one of the most popular sports in the United States. However, in comparison to other mainstream sports such as soccer and rugby, there is limited literature using scientific principles and theory to examine the most appropriate ways to monitor the sport. This serves as a barrier to American football practitioners in their development and implementation of evidence-based sport preparation programs. Therefore, the primary aim of this line of research (i.e., dissertation) is to illustrate the efficacy of commonly used athlete monitoring tools within the sport of American collegiate football, while proposing a systematic framework to guide the development of an athlete monitoring program. This aim was achieved through a series of studies with the following objectives: 1) to quantify the physical demands of American collegiate football practice by creating physiological movement profiles through the use of integrated microtechnology metrics and heart rate indices, 2) to determine the positional differences in the physical practice demands of American collegiate football athletes, 3) to examine which integrated microtechnology metrics might be used to most efficiently monitor the training load of American collegiate football athletes, 4) to demonstrate the suitability of using the countermovement jump (CMJ) to assess training adaptations in American collegiate football athletes through examining weekly changes in CMJ performance over the course of two 4-week periodized training blocks (8 weeks total), and 5) to examine the effect of acute fatigue on CMJ performance in American football athletes. The first study from this line of research quantified the physical demands of American collegiate football by position groups and found significant differences in both running based and non-running based training load metrics. In addition, the first study utilized a principal component analysis to determine 5 'principal' components that

explain approximately 81% of the variance within the data. The second study utilized a univariate analysis and found significant changes in CMJ performance due the effect of time with significant improvements in CMJ ‘strategy’ variables over the training period. Finally, the third study used effects sizes to illustrate a larger magnitude of change in CMJ ‘strategy’ variables than CMJ ‘output’ variables due to effect of acute fatigue. Results from studies 2 and 3 suggest the importance of monitoring CMJ strategy variables when monitoring training adaptations and fatigue in American collegiate football athletes. This line of research provides practitioners with a systematic framework through which they can develop and implement evidence-based sport preparation programs within their own organizational context. In addition, this line of research provides practitioners with recommendations for which metrics to monitor when tracking training load in American collegiate football using integrated microtechnology. Finally, this line of research demonstrates how to assess training adaptations and fatigue using the CMJ within the sport of American collegiate football, while providing an empirical base through which the selection of CMJ variables can take place. Collectively, this line of research uses scientific principles and theory to extend the current literature in American collegiate football, while providing practitioners with a guide to athlete monitoring within the sport.

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General Audience Abstract

American football is one the most popular sports in the United States. Despite its popularity, there is limited research using scientific principles and theories to examine ways to most effectively monitor the sport. Broadly, athlete monitoring refers to the process of providing informational feedback from the athlete to practitioners. This allows practitioners to make decisions informed by data. Therefore, this line of research (i.e. dissertation) aimed to use a variety of commonly used athlete monitoring tools to monitor American collegiate football athletes, while proposing a framework to guide in the development of an athlete monitoring program. This line of research consisted of a series of 3 studies. In study #1, it was found that integrated microtechnology units and heart rate sensors could be used to determine the physical demands of American collegiate football practice, as well as differences in the physical demands of practice by position group. In addition, a set of 5 training load constructs were found through which training load in American collegiate football athletes may be appropriately monitored. In study #2, it was found that countermovement jump (CMJ) strategy variables indicating *how* the jump occurred may provide more insight into strength and power training adaptations than CMJ output variables that indicate *what* occurred as a result of the jump in this highly trained athletic population. Finally, in study #3, it was found that CMJ strategy variables may be more sensitive to acute fatigue from a football-specific training session than CMJ output variables in American collegiate football athletes. Collectively, this research suggest that integrated microtechnology units, heart rate sensors, and the CMJ using a force testing platform may be used to monitor American collegiate football athletes. Moreover, this research suggests which variables to utilize

when monitoring this population using these tools through the proposed athlete monitoring framework.

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research ideas, and supported my applied sports science intern program within Virginia Tech athletics.

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Table of Contents

List of Figures

List of Tables

Organization and Structure

This dissertation—hereafter referred to as a line of research—proposes an athlete monitoring framework and demonstrates its use within the sport of American football through a series of studies, and is organized into 5 chapters. Chapter 1 consists of an introduction to the research problem, a statement of the research aim, and descriptions of the objectives through which the research aim will be addressed. Chapter 2 consists of a literature review on the physiological characteristics and physical demands of American football, an overview of the conceptual framework guiding the review, and the introduction of a proposed athlete monitoring framework with sections addressing the theory guiding the framework and descriptions of its constructs.

Since this line of research uses the same instruments, the same variables, and draws from the same population, chapter 3 provides an overview of the general methods that will be used in all studies. Chapter 3 also consists of a specific methods section which allows for each study's distinct design and analytical approach to be described. Chapter 4 provides results for each study, as well as a discussion of the results for each specific study. Finally, chapter 5 provides a general discussion and illustrations of the practical application of this line of research to the sport of American football.

Glossary

Term	Definition
Concentric	Describes a muscle contraction that produces force as it shortens, during either flexion or extension of a specific joint. In terms of jump analysis, the concentric phase represents the time period between the lowest point of the center of mass depth and takeoff from the force plates. This is the upward phase or triple extension component of the jump.
Contraction Time	Total measured time from the start of the movement until takeoff. For the countermovement jump, this encapsulates both eccentric and concentric phases.
Eccentric	Describes a muscle contraction that produces force as it lengthens during either flexion or extension of a specific joint. In term of jump analysis, the eccentric phase represents the time period between the start of the movement and the lowest point of the center of mass depth. This is the downward phase that generates/builds elastic energy for use during the concentric phase.
Flight Time-to-Contraction Time Ratio (FT:CT)	A simple ratio of jump performance to preparation time needed. In a sporting context, it is desirable for an individual to achieve significant vertical jump performance (i.e., elevated flight time, power output, and peak velocity) with the least amount of time required. Increases in this ratio are due to improved jump ability and/or reduced preparation time (defined as from the start of movement to take off.
Impulse (I)	The action of a force over a period of time which leads to a change in momentum (velocity) of the athlete. Impulse reflects the area under the force-time curve. It is calculated. I = F x t.
Jump Height (JH)	The net displacement of the center of mass from the instant of take-off to the peak displacement (as a result of the net concentric impulse generated on the force plate in the preceding movement). Calculated from the impulse-momentum equation. JH = ½ x (velocity at take off^2/9.81m/s^2).

Reactive Strength Index Modified (RSI^{mod})	RSI^{mod} = JH/contraction time
Relative Mean Power (RMP)	RMP = (F.v)/body mass in kg
Velocity (V)	$V = v_0 + a.t$

Chapter 1

Introduction

American football is one of the most popular sports in the United States. As noted by Hoffman (2008), "its popularity is likely related to the intense, fast-paced, physical style of play" (p. 1). Regardless of the level of play, American football is played on a 100 by 53.3 yard field. At the collegiate level in the National Collegiate Athletics Association (NCAA), the game consists of four 15 minute quarters separated by a halftime period of 20 minutes (12 minutes in the National Football League [NFL]). During the in-season period of competition, teams competing in the NCAA typically compete in 12 regular season games. Depending upon their level of success during the regular season, a team competing in the NCAA could compete in up to 3 additional games for a total of 15 games.

The objective the game is to accumulate more points than your opponent. To achieve this objective, the offense attempts to drive the ball down the field and score either a touchdown (6 points) or a field goal (3 points). Meanwhile, the defense attempts to prevent them from scoring. The defense can also score by way of a touchdown or safety (2 points). The winning team is the one that accumulates the most points over the course of the game. If the teams are tied after the regulatory period, the teams will then compete in an overtime period. At the collegiate level, the overtime periods of played in a condensed area of the playing field and allow both teams the opportunity to score.

From a physical perspective, American football is a field-based sport that consists of intermittent, high-intensity bouts of activity, which are followed by periods of recovery (Iosia & Bishop, 2008; Rhea, Hunter, & Hunter, 2006). During the periods of recovery, teams will substitute players in and out of the game with the goal of putting in players that give them the best chance to gain yards on next play if on offense, or prevent the opposition from gaining yards if on defense. In terms of physical movement, American football requires repeated bouts of sprinting, backpedaling, accelerating, decelerating, and physical collisions (Hoffman, 2008). However, the number and magnitude of these physical movements may differ based on the various positional demands (Edwards, Spiteri, Piggott, Haff, & Joyce, 2018; Wellman, Coad, Goulet, & McLellan, 2016).

While a description of the physical characteristics of the sport and the activities required for competition is vital, a deeper understanding of the physiological and biomechanical demands of the sport allow practitioners to more appropriately design physical training programs and monitor their athletes for optimal health, wellness, and performance (Joyce & Lewindown, 2014; McGuigan, 2017). Researchers have attempted to examine the physical requirements of the sport by interpreting data from tests of anthropometrics (Anzell, Potteiger, Kraemer, & Otieno, 2013) and physical qualities of American football players (Davis et al., 2004; Fry & Kraemer, 1991; Garstecki, Latin, & Cuppett, 2004). Meanwhile, more recent scholarship has examined the physical demands of American football using integrated microtechnology (DeMartini et al., 2011; Wellman et al., 2016; Wellman et al., 2017).

Wellman et al. (2016, 2017) monitored 33 division I American football players during 12 regular season games, which allowed the authors to create physiological movement and impacts profiles for offensive and defensive position groups. While Wellman and colleagues examined the game demands of American collegiate football, DeMartini et al. (2011) investigated the practice demands of division I American collegiate football players during the first week of preseason camp using integrated microtechnology and heart rate. Finally, Ward (2018) investigated the physical demands and training load metrics for the use of athlete monitoring in the NFL, which was a novel exploration of the physical demands of American football at the professional level.

The use of integrated microtechnology for athlete monitoring is well established in sports such as soccer and rugby (Taylor, Chapman, Cronin, Newton, & Gill, 2012). However, microtechnology has been employed as an athlete monitoring strategy to a lesser degree in American football (Ward, 2018; Wellman et al., 2016). As noted by Ward (2018), "the scientific literature that has focused on the physical demands of American football is small" (p. 9). Thus, future research focused on quantifying the physical demands of American football, while exploring how athletes may be most appropriately monitored within the sport, is of relevance to both practitioners and scholars, alike.

While the monitoring of the physical demands of the sport and the subsequent training load of the athlete is critical, the assessment of fitness and fatigue is a foundational domain within any athlete monitoring program (Joyce & Lewindon, 2014; McGuigan, 2017). The countermovement jump (CMJ) has been widely used by practitioners as means through which they can assess adaptations to training and athlete fatigue (Taylor, Chapman, Cronin, Newton, & Gill, 2012), and is frequently employed in research studies on monitoring neuromuscular status (Claudino et al., 2016). While numerous investigations have assessed adaptations to training and fatigue in other sports (Cormack, Newton, McGuigan, & Cormie, 2008; Gathercole, Sporer, & Stellingwerff, 2015a; Gathercole, Sporer, Stellingwerff, & Sleivert, 2015b; Gathercole, Stellingwerff, & Sporer, 2015c; Hoffman, Nusse, & Kang, 2003; Kennedy & Drake, 2017), there have been fewer examinations of athlete fatigue using the CMJ in American football (Hoffman et al., 2002).

In addition, to the author’s knowledge, there have been no investigations into monitoring athlete adaptations to training or fatigue in American football using CMJ mechanic variables (or ‘jump strategy’ variables). The vast majority of studies across all sports assessing these outcomes using the CMJ analyze only physical output (or ‘jump output’) variables such as jump height, peak velocity, and concentric power and force indices (Claudino et al., 2016; Gathercole 2015c). However, there have been examinations in athletic populations that have demonstrated the efficacy of monitoring jump strategy variables for purpose of monitoring fatigue and adaptations to training (Cormie et al., 2010a, b; Gathercole et al., 2015a, b, c; Kennedy & Drake, 2017). Thus, examinations exploring these outcomes using the CMJ in American collegiate football would guide practitioners in their utilization of athlete monitoring tools, as well as extend the current knowledge base in the sport.

One potential resource to assist practitioners in understanding the interaction between athletes and physical performance outcomes within their sport is through the development of an athlete monitoring program (Coutts & Cormack, 2014). Broadly, an athlete monitoring program provides feedback pertaining to the quantity and quality of training and competition, level of athlete fatigue and fitness, information regarding non-training parameters such as athlete wellness, nutrition, and sleep, and individual factors such as athlete training and injury history (Coutts & Cormack, 2014; McGuigan, 2017). While most all elite sporting programs engage in some type of monitoring, there is limited literature suggesting how to efficiently and effectively monitor athletes in the sport of American football (Edwards et al., 2018; Ward, 2018; Wellman et al., 2016, 2017). Moreover, with advancements in technology, establishing a comprehensive athlete monitoring program is now time efficient and financially feasible for amateur sporting programs, as well as professional teams (McGuigan, 2017).

Research Aim and Objectives

The overall aim of this line of research is to determine the efficacy of commonly used athlete monitoring tools within the sport of American football, while demonstrating the suitability of a systematic framework to monitor athletes. This will be achieved through the following objectives:

1. To determine if the physical demands of American collegiate football can be quantified using physiological movement profiles developed through the use of integrated microtechnology metrics and heart rate indices.
2. To determine if physiological movement profiles can be used to quantify positional differences in the physical demands of American collegiate football practice.
3. To examine if there is a subset of integrated microtechnology metrics that can be used to efficiently monitor the training load of American football athletes.
4. To determine if countermovement jump performance changes in response to a 8-week periodized training program focusing on strength, speed, and power abilities in American collegiate football athletes.
5. To determine the effect of acute fatigue on countermovement jump performance in American collegiate football athletes.

Limitations and Delimitations

As with all research, there are certain limitations and delimitations that apply to this line of research. Limitations being described as those factors outside of the researcher's control that may be potential threats to internal and external validity. Meanwhile, delimitations can be described as intentional choices made by the researcher that influence the inferences that can be made from research findings.

Limitations

1. Due to the use of observational data and associational analyses, causal inference may not be drawn from these research findings.
2. When using jump testing for assessing neuromuscular abilities, there is an assumption that maximal effort is given by the participant.
3. As with all applied sport science research, the sampling strategy utilized in this line of research—purposive sampling—was a non-probability method. Thus, the sample may not be representative of the population (Henry, 1990).
4. These data are observational data in which the researcher did not have control over the type of training completed, the duration of the training, or the frequency with which the training was completed.

Delimitations

1. Findings from this line of research are limited to American collegiate football athletes at the division I level.
2. Data collected from practices and training sessions are specific to the population under examine, and thus, generalizability is limited.

Chapter 2

American Football

The purpose of this section is to introduce the conceptual framework through which a literature review on the sport of American football will take place and to critically analyze the literature exploring the physical demands of American football. Since the body of literature on American football is limited, literature from other teams sports will be reviewed, and analyzed, where applicable.

Conceptual Framework

As noted by Ward (2018), “the physical demands of a sport can be understood through the application of one, or all, of three main methodological approaches: (1) understanding the physical characteristics of individuals who participate in the sport; (2) the observation of matches and training; (3) the monitoring of players during competition or training” (p. 10). Using these different theoretical approaches, scholars have explored the physical demands of American football while identifying key attributes that are specific to the sport (Fry & Kraemer, 1991; Garstecki, Latin, & Cuppett, 2004), as well quantifying the demands associated with both training (DeMartini et al., 2011) and actual competition (Wellman et al., 2016; Wellman et al., 2017). Indeed, employing these theoretical approaches allow for a better understanding of the physical demands of American football through describing the physical qualities of the athletes and quantifying the work completed during both training and competition.

Physical characteristics of individuals who participate in American football

The physical qualities and performance characteristics of American football athletes has been investigated by several researchers at differing levels of competition. While there are differences in these qualities and characteristics based on the level of competition, it is clear that the strength, power, and speed abilities dominant the sport of American football (Davis, Barnette, Kiger, Mirasola, & Young, 2004; Fry & Kraemer, 1991). In addition, it appears that coaches have prioritized training these qualities in today's American football athlete (Secora, Latin, Berg, & Noble, 2004).

Fry and Kraemer (1991) examined the physical qualities of American collegiate football players from nineteen different NCAA institutions. Using these data, Fry and his colleague compared the performance tests (1 RM bench press, 1 RM back squat, 1 RM power clean, vertical jump, and 35.6 meter sprint) of collegiate football players by position, playing ability, and caliber of play. The authors reported that there were statistically significant differences in performance measures when comparing collegiate football players by position. Moreover, the authors noted statistically significant differences in measures of performance based on the level of competition (e.g., division I, II, or III). Finally, the authors found that by position groups starters performed superior to non-starters on all performance measures except for the back squat (Fry & Kraemer, 1991).

Davis and colleagues (2004) examined the relationship between 6 physical characteristics (height, weight, bench press, sit and reach, hang clean, and body composition) and 3 functional measures (36.6 meter sprint, vertical jump, and 18.3 meter shuttle run) in division I college football players using stepwise multiple regression. The authors reported clear prediction models for the 36.6 meter sprint and the 18.3 meter shuttle run. While body weight negatively impacted both the sprint and the shuttle run, the bench press and hang clean were found to be positively related to these performance tests. Meanwhile, the sit and reach was negatively correlated to the shuttle run suggesting that as hamstring length increases, the shuttle run time decreased (e.g., better performance).

Secora and company (2004) compared the physical and performance characteristics of division I football players from 1987 to those of 2000 using normative data captured through survey questionnaires. In this examination, the authors found that, in general, division I football players had become bigger, faster, and stronger with significant improvements in strength, power, and speed measurements, as well as enhancements in body composition despite increased levels of body weight (i.e., increased fat-free mass).

While there are a host of limitations in this investigation including self-reporting these data and other factors influencing these outcomes such as educational awareness regarding sports nutrition and supplementation, it appears that coaches at all levels of competition have emphasized training strength, power, and speed qualities American football players with the assumption that this translates into elevated levels of performance in their sport.

Observation of matches and training

Rhea, Hunter, and Hunter (2006) conducted one of the first descriptive analyses of collegiate American football using observational data to provide a competition model for American football. The purpose of their investigation was to construct a competition model of American football for 3 different level of play: high school, college, and professional. This observational research expanded on the work of Plisk and Gambetta (1997) who deconstructed the physical demands of two NFL teams by evaluating their competitions during the 1991-92 playoffs. Rhea and his colleagues found that the average time of a run play was the longest in high school (5.60 seconds) and the shortest in college (5.13 seconds), while the average time of a pass play was the longest in college (5.96 seconds) and the shortest in high school (5.68 seconds).

In addition, the average recovery between plays was the longest in the NFL (35.24 seconds) and the shortest in high school (31.49 seconds) with recovery due to stoppage the longest in the NFL (112.59 seconds), as well. Thus, the average work-recovery ratio was the longest in the NFL (1:6.2) and the shortest in high school (1:5.48) with collegiate football splitting the difference at a 1:6.07 work-recovery ratio. As pointed out by Plisk & Gambetta (1997) and reiterated by Rhea, Hunter, & Hunter (2006), the competition modeling procedure has a couple of inherent limitations regarding its ability to accurately portray the physical demands of sport.

First, the identified work-recovery ratio may not accurately reflect the full extent of an athlete's work output in competition because activity does not necessarily stop altogether at the conclusion of a play. Moreover, the work performed during both the work and the recovery periods differ by position. For example, a wide receiver may jog 30-40 yards back to the huddle after a play while a lineman walks 5-10 yards back to the same huddle. Second, a competition model does not provide a direct assessment of the physical work completed during competition, nor does it provide a direct measure of the rate at which that work was completed (i.e., competition intensity).

Similar to Rhea and colleagues (2006), Iosia and Bishop (2008) conducted an examination of the mean duration of exercise-to-rest ratios during the course of several televised games, while accounting for style of play. The authors categorized all teams in the 2004 final Top 25 Coaches Poll into either a run, pass, or balanced style offense by determining the percentage of run and pass plays out of the total number of plays run over the course of the season. After categorizing the top 25 teams, the authors selected two teams representing each style of play category to include in their analysis (Iosia & Bishop, 2008).

Iosia and Bishop (2008) found that the average duration of a play was 5.23 seconds, while the average duration of a run and pass play were 4.86 and 5.60, respectively. The authors found running plays to be statistically shorter in duration than passing plays. Moreover, the authors reported that the average duration of a play based on the style of play (i.e., run, pass, or balanced) was 4.84, 5.41, 5.44 seconds, respectively; there was a statistically significant difference in the duration of a play based on the style of play.

Meanwhile, Iosia and Bishop (2008) found that the overall mean for duration of rest between plays was 46.9 seconds with a standard deviation of 34.3 seconds; there were no significant differences reported between groups. However, due to the large standard deviations, the authors excluded rest durations longer than 1 minute (i.e., extended rest durations) and found an average duration of rest between plays of 36.09 seconds with a much smaller standard deviation of 6.71 seconds. The average duration of rest based on the style of play for run, pass, and balanced teams were 35.06, 38.08, and 35.21 seconds, respectively; there was a statistically significant difference found between groups. In addition, the authors reported an overall duration of rest between series of 11.30 minutes with no significant differences based on the style of play.

The average duration of play (5.23 seconds) reported by Iosia and Bishop (2008) was similar to that reported by Rhea, Hunter, and Hunter (2006). The duration of recovery between plays was similar in these two investigations when considering the exclusion of extended recovery periods longer than 1 minute by Iosia and Bishop (2008). Thus, the work-recovery ratio reported by Rhea and colleagues of 1:6.07 for college football is quite similar to the work-rest ratio reported by Iosia and colleague of 1:7. However, if extended periods of rest are included, it can be suggested that work-rest ratios of 1:8 to 1:10 are more reflective of the work-rest ratios in American football (Iosia & Bishop, 2008).

Iosia and company (2008) reported an average duration of rest time between series of 11.30 minutes, which was the first reported measurement of the duration of rest time between series in the peer-reviewed literature. Determining the average duration of rest between series has significant implications for exercise prescription, as many strength and conditioning professionals prescribe interval type training for the purpose of conditioning. Thus, these data provide insight into how the prescription of such intervals could be tailored to match the physical demands of American football.

The limitations of Iosia and Bishop's examination of work-rest ratios in American football is similar to the limitations in Rhea and company's study. While a competition model is useful, there is no direct assessment of the physical work completed by the athletes during competition, nor the rate at which the work was completed. While football is high-intensity, intermittent sport, there may be differences in the work completed during the play, as well as differences in the work completed during recovery, which alter the physical demands required for competition by differing position groups. Finally, unlike Rhea and colleagues, Iosia and Bishop (2008) examined the work-rest ratios of American football at only one level of competition (college). Thus, the results of their examination may not be generalized to other levels of competition.

Monitoring of players during competition and training

In the first published report of using integrated microtechnology to monitor American football athletes, DeMartini and colleagues (2011) used GPS technology to examine the physical demands imposed on Division 1 football players during preseason training in hot conditions. The authors divided the forty-nine male football players into two groups: linemen and non-linemen, and starters and non-starters. DeMartini and company reported that the total distance covered was significantly higher in non-linemen than in linemen, while the total distance was significantly higher in starters when compared to non-starters during team drills only; no significant differences were found in total distance covered during position drills or total practice duration.

Meanwhile, DeMartini and colleagues went on report that non-lineman spent a higher percentage of their total distance in lower velocity zones when compared to lineman, while there were no significant differences in the percentage of total distance spent in any velocity zone when comparing starters to non-starters. Finally, non-lineman reached a higher heart rate max during position drills and total practice duration when compared to lineman, however there were no significant differences in heart rate max during team drills and no significant differences in average heart rate in position drills, team drills, or total practice duration.

DeMartini et al. (2011) was the first peer reviewed publication quantifying the physical demands of American football using GPS technology. Thus, the findings were enlightening. However, it is important to note several of the delimitations to these findings. First, it is important to note that each players data was only used once for statistical analysis. Hence, each data point was from only 1 preseason practice session. Second, these data are from the first 8 days of preseason camp, in which the physical demands of practice are very different than most football practices due to the required acclimation period. Finally, starters and non-starters were one of the comparison groups. However during the first week of preseason camp, all starters and non-starters may not be determined yet, and for the ones that have, they may not be engaging in differential training loads yet due to the timeframe in which these data were collected.

Wellman, Coad, Goulet, and McLellan (2016) expanded upon the work from DeMartini and colleagues by examining the competitive physiological movement demands of NCAA

Division 1 college football players during games using GPS technology. Moreover, the authors examined positional groups within offensive and defensive categories to determine if a player's physiological requirements during games were influenced by their playing position. Of note, the authors analyzed data that were collected for each of the twelve regular season games.

Wellman and company found that the wide receiver position covered more total distance, moderate intensity and high intensity distance, and sprinting distances that all other offensive positions; wide receivers, running backs, and quarterbacks achieved a significantly higher average maximal speed than either the tight ends or offensive lineman with wide receivers achieving a significantly higher average maximal speed than any other offensive position. Meanwhile, defensive backs and linebackers covered more total distance, moderate and high intensity distance, and sprinting distance than either defensive ends or defensive tackles; defensive backs had the highest average maximal speed than any other defensive position.

In comparison to the findings reported by DeMartini and colleagues (2011), the results presented by Wellman et al. (2016) indicate that the total distance covered for both lineman (3,624 yards) and non-linemen (4,528 yards) during games is greater than the total distance covered by lineman (2,813 yards) and non-linemen (3,862 yards) in the findings by DeMartini et al. (2011). However, these findings are consistent insofar that non-lineman cover more total distance than linemen. The findings by Wellman and company investigating the intensity of the total distance covered by positional groups were similar to those by DeMartini, in which the authors reported that non-lineman covered significantly more high intensity distance when compared to linemen.

The work by Wellman and colleagues (2016) contributed significantly to the literature on the physical demands of American football and built upon the work by DeMartini and company

(2011) through using GPS technology to monitor the physical demands of competition in the sport. Of note, Wellman and his colleagues used speed of locomotion and acceleration/deceleration as markers of competition intensity. While these external load markers are extremely helpful, they do not provide insight into the athlete's response to a given load (i.e., internal load). Therefore, the quantified high intensity efforts simply determine the amount of work completed and do not indicate the relative training intensity of the athletes. In other words, a high intensity running distance (16.1-23 km/hr. in this study) may not elicit the same internal response for a wide receiver as tight end. Furthermore, these intensity values will differ based on the individual's fitness level, state of readiness for that day, and non-training related parameters.

Using GPS and integrated accelerometer technology, Wellman, Coad, Goulet, and McLellan (2017) examined the positional impact profiles of NCAA Division 1 college football players and determined if there were positional differences in impacts profiles during competition between offensive and defensive teams. The authors classified impacts on a scale of very light (5.0-6.0 G force) to severe (>10.0 G force). Impacts were derived from the vector of the X-Y-Z axes of the triaxial accelerometer and calculated as the square root of the sum of the squares of each axis (Wellman et al., 2017).

With a sample of thirty-three athletes, the authors found that on offense the wide receiver group sustained more very light and moderate impacts than all other offensive position groups, while the offensive linemen sustained more very light impacts than either running backs or quarterbacks. The wide receiver, offensive linemen, and tight end position groups sustained significantly more moderate-to-heavy (6.6-7.0 G force) impacts than the quarterback and running back position groups. While there were no statistical differences between position groups for very heavy (8.1-10.0 G force) impacts, there were significant differences in severe impacts by position groups with the running back position having a significantly higher number of severe impacts than the wide receiver, tight end, and offensive linemen position groups. Moreover, the quarterback position group had a significantly greater number of severe impacts than the tight end position group.

In terms of defensive position groups, the defensive back position group sustained significantly more very light impacts than the defensive tackle and defensive end position groups, while the linebacker position group was involved in significantly more very light impacts than the defensive tackle position group. Meanwhile, the defensive tackle position group was involved in significantly more moderate-to-heavy (6.6-7.0 G force), heavy (7.1-8.0 G force), and very heavy (8.1-10.0 G force) impacts than all other defensive position groups, while the defensive end position group sustained significantly more heavy and very heavy impacts than the defensive back position group. There were no significant differences between position groups within either the light-to-moderate (6.1-6.5 G force) or the severe (>10 G force) impact zones.

The examination by Wellman and colleagues (2017) on impact profiles within the sport of American football was the first of its kind. While these findings are novel within the American football literature, these findings are similar to those within Rugby League (McLellan & Lovell, 2012; McLellan, Lovell, & Gass, 2011) and Rugby Union (Cunniffe, Proctor, Baker, & Davies, 2009; Suarez-Arrones et al., 2012) demonstrating inter-positional differences in the quantity and intensity of impacts during competition.

Athlete Monitoring

The purpose of this section is to describe athlete monitoring, outline a variety of strategies utilized by practitioners to monitor athletes, and to propose an athlete monitoring framework to guide practitioners in their monitoring-related decisions. Due to the breadth of athlete monitoring strategies, an overview will be provided for all topical areas with the areas directly related to this line of research expanded to their necessary depths.

Generalized Theories of Training

The physiological rationale underpinning athlete monitoring is best described with an overview of select theories that have been developed into models and used to explain the physiological effects of training stress. These models include the general adaptation syndrome (GAS) model, the fitness-fatigue model, and the stimulus-fatigue-recovery-adaptation model. These models provide a basic understanding of the interplay between training stress, resultant fatigue, adaptations, and fitness.

Canadian physiologist, Hans Selye, conceptualized the GAS model with his pioneering work understanding the physiological effects of stress (Selye, 1950). The central tenant of his work was based on the understanding that when stressors are introduced to the human body there is a disruption in homeostasis, which results in a chain of events involving both damage and defense (Selye, 1950, 1956). The model itself is described in 4 phases: 1) phase 1 – alarm or shock during the initial response to stress, 2) resistance with adaptations occurring, 3) supercompensation with a new level of adaptation, and 4) overtraining, if stressors continue at too high of a level with insufficient recovery (McGuigan, 2017).

The purpose of training is to provide a stimulus (stress) that disrupts homeostasis, which initiates a cascade of cellular, and subcellular events, allowing for physiological adaptations to occur. A result of these adaptations is a higher level of fitness due to the training effect, which is commonly referred to as supercompensation (Zatsiorsky & Kraemer, 2006). While the human body is extremely adaptable, phase 4 of the GAS model illustrates that overtraining can occur if too much training stress is introduced over a prolonged period of time without sufficient recovery.

The fitness-fatigue model, otherwise known as the two-factor theory of training, is based on the idea that preparedness, which is characterized by an athlete's potential sport performance, is not stable but rather varies with time (McGuigan, 2017; Zatsiorsky & Kraemer, 2006). Time is a vital component of this description as the two factors within this model have varied latency periods of effects. While fatigue (discussed in detail later within this chapter) has fast changing, immediate effects that can be altered in the matter of seconds, minutes, or hours, physical fitness is a slow changing component of an athlete's preparedness (Zatsiorsky & Kraemer, 2006).

Since fatigue is fast changing with immediate effects, an athlete's preparedness can be quickly altered resulting in a deterioration in performance. While improvements in fitness is the ultimate aim of introducing training stress, there must be considerations given to the interplay between these two factors. As noted by Zatsiorsky and Kraemer (2006). "an athlete's preparedness is sometimes thought of as a set of latent characteristics that exist at any time but can be measured only from time to time" (p. 12). Based on this model, the final outcome of performance-related measures can be described as a summation of the positive and negative changes in athlete preparedness at the given point in time these measures are taken.

Finally, the stimulus-fatigue-recovery-adaptation model describes a general response following the application of a training stimulus (McGuigan, 2017). This model can be outlined in 5 interrelated phases: 1) stimulus (training load), 2) fatigue (accumulation of loading), 3) recovery (return to homeostasis), 4) supercompensation (peaking), and 5) involution (preparedness and performance). Similar to the models previously described, the stimulus-fatigue-recovery-adaptation model illustrates the interplay between training stress, fatigue, recovery resulting in adaptations, and ultimately increased levels of fitness and performance (McGuigan, 2017).

A description of these generalized training theories provide the basis on which the purpose and importance of athlete monitoring is based. While all of these theories (models) have their own unique characteristics, they all outline the importance of achieving a balance between the dose of training stressors, the resultant fatigue and subsequent recovery, and the degree of adaptations and level of fitness. These theories guided the conceptualization of the athlete monitoring framework proposed by the author, and provides the physiological rationale that underpins the constructs within the framework.

Athlete monitoring allows for feedback from the training process. The aim of the training process is to provide a stimulus by which the athlete is stressed and an adaptation specific to the stress is elicited (Coutts & Cormack, 2014; McGuigan, 2017). However, as noted by Coutts and his colleague, "training and performance share a complex relationship based on several factors, many of which are unique to the individual athlete and performance task" (Coutts & Cormack, 2014, p. 71). Thus, athlete monitoring serves as a way, through which, the individuality of the training process can be accounted for and the training stimulus can be altered based on the response to training.

To understand the training process, it is vital to understand how a prescribed training dose (i.e., training and competition load) will produce a specific physiological response (Coutts & Cormack, 2014). Once the training dose-response relationship is understood, practitioners can more effectively prescribe training stressors that target adaptations specific to the physical demands of their sport. Understanding the dose—response relationship, and ultimately the training process, requires practitioners to have reliable, valid, and sensitive feedback from athletes during both training sessions and competition.

In addition to the training dose, there are other important factors to assess when monitoring the training process including athlete fatigue and fitness, existing modifiable and non-modifiable individual factors, and non-training parameters (McGuigan, 2017). These factors work in a complex and dynamic nature with each one influencing the other. For example, recovery is a multifaceted, restorative process that is relative to time and impacts an athlete's process of adapting to a training stimulus, as well as their readiness for a new stimulus (Kellman et al., 2018). Thus, assessing athlete fatigue and fitness provides feedback regarding the athlete's response and adaptation to a training dose and program, as well as feedback regarding the athlete's position on the recovery—fatigue continuum; also referred to as 'training readiness' (Fomin & Nasedkin, 2013; Kellman et al., 2018).

Training readiness can be described as the current functional state of an athlete that determines the ability of an individual to effectively achieve their performance potential (Fomin & Nasedkin, 2013). Meanwhile, non-training parameters can be described as what is happening outside of training and competition such as athlete nutrition, sleep, hydration, and wellness, and can provide insight into specific factors influencing the athlete's position on the recovery—fatigue continuum (Kellman et al., 2018; McGuigan, 2017). It is suggested that a combination of both subjective and objective measures is most effective at providing an overall picture of the athlete's readiness to train and their position on the recovery—fatigue continuum (Halson, 2014; McGuigan, 2017).

A key purpose of monitoring an athlete's acute response to a given training dose is to gauge their chronic adaptation to the training stressors provided during a training cycle

(McGuigan, 2017). Typically, pre-testing and post-testing is an effective way to gauge an athlete's progress during a training cycle. However, if the training cycle is >6 weeks, testing should be administered during the training cycle to prevent from missing crucial information regarding the athlete's response (Coutts & Cormack, 2014). As noted by McGuigan (2017), pre-testing and post-testing does the following:

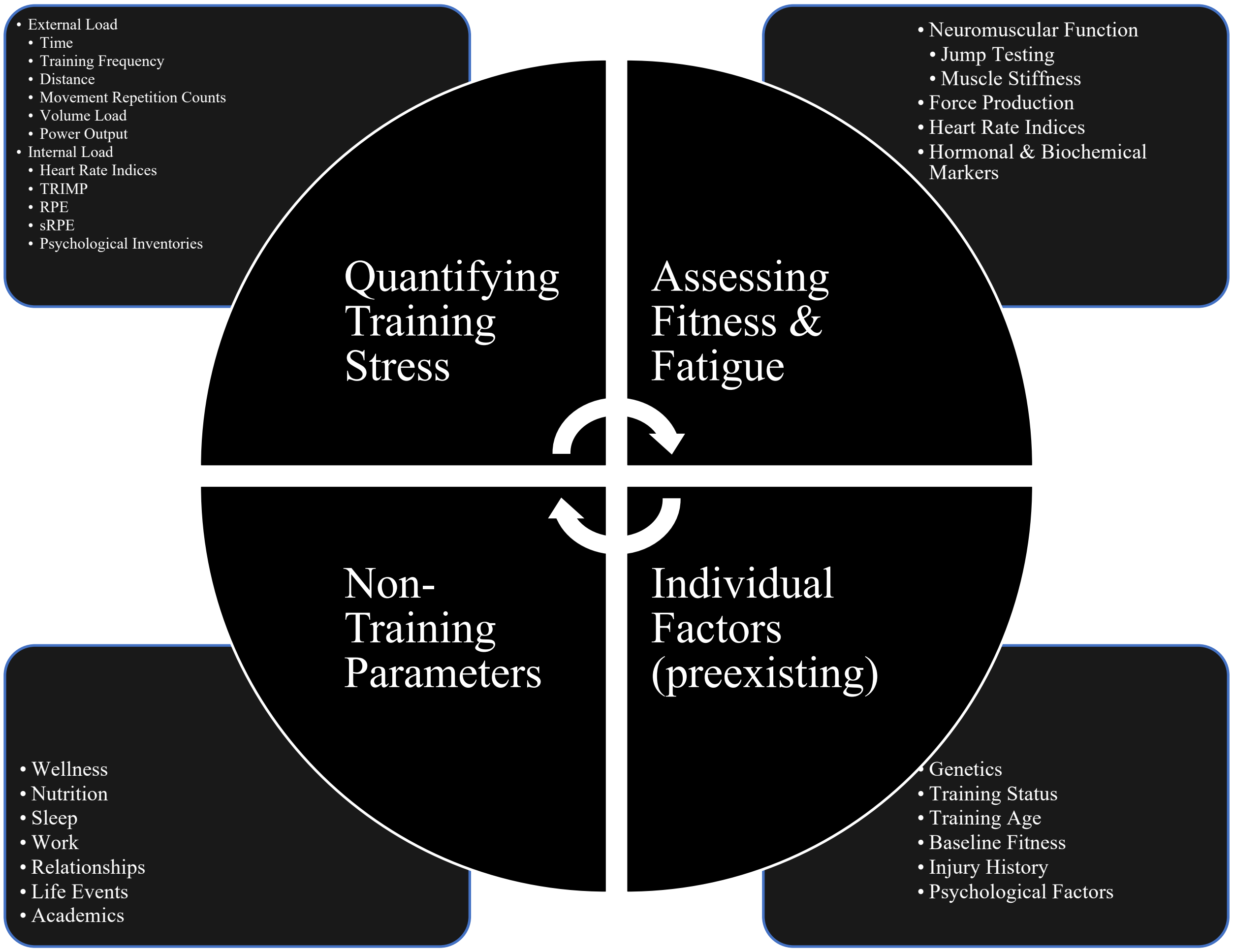
- Provides objective data on the effects of the training program
- Assesses the impact of a specific type of intervention
- Helps the practitioner make informed decisions about changes to the training program
- Identifies the physical strengths and weaknesses of the athlete
- Maximizes the practitioner's and athlete's understanding of the needs of the sport
- Adds to the body of knowledge on high-performance athletes

While pre- and post-testing allow for the effectiveness of a training program, and the chronic response of the athlete, to be evaluated, physical qualities such as strength and power can change rapidly. Moreover, training readiness varies which can result in daily variations of the athlete's response to a given stimulus. Thus, an athlete can be prescribed a training dose, or stimulus, to which they are not ready to respond.

For example, it has been shown that there is a large daily variation in maximal strength and perception of effort for a given relative load (Zourdos et al., 2016). Indeed, predetermined training stimuli may provide athletes with an inadequate training dose, which has been shown to be less effective than more 'fluid' methods in which a training dose is determined based on an athlete's level of readiness and adaptability (Morris, 2015). Thus, day-to-day monitoring of the acute response within a training cycle allows for regular feedback about how the athlete is adapting to the training program, while accounting for daily variations in the training response.

Figure 2.1 provides an overview of the athlete monitoring cycle, as conceptualized by the author in a proposed athlete monitoring framework.

Figure 2.1 Athlete Monitoring Framework



Athlete Monitoring: Quantifying Training Stress

Monitoring the quantity and quality of the stress of training and competition is essential to understanding the training dose—response relationship, assessing athlete readiness, and determining whether or not an athlete is adapting to their training program. McGuigan (2017) defined training load as “the measure of total training stress experienced by the athlete” (p. 4).

Measures of training load can be categorized as either internal or external. Internal training loads can be described as “the relative biological (both physiological and psychological) stressors imposed on the athlete during training or competition” (Bourdon et al., 2017, p. S2-161). Meanwhile, external training loads can be described as “objective measures of the work performed by the athlete during training or competition and are assessed independently of internal workloads” (Bourdon et al., 2017, p. S2-161).

Common measures of internal training load include heart rate, rating of perceived exertion (RPE), oxygen consumption, and blood lactate. Meanwhile, common measures of external training load include GPS and accelerometer parameters such as total distance, high speed running, change of direction actions such as accelerations and decelerations, mechanical power output, metabolic power, and volume load (Bourdon et al., 2017; McGuigan, 2017). Although the assessment of training load is dependent upon the characteristics of the training program and sport, an integrated approach is most effective for providing a comprehensive understanding into the training load of an athlete (Bourdon et al., 2017).

Athlete Monitoring: Assessing Fitness and Fatigue

Fitness and fatigue are very broad terms that are defined based on the contextual environment in which they are used (Coutts & Cormack, 2014). Due to the focus within in this line of research, this subsection will focus on monitoring athlete fitness and fatigue through the assessment of neuromuscular status. There will be a broader discussion of fatigue in terms of the relationship between fitness and fatigue in a later subsection.

Neuromuscular fatigue can be described as the reduction in maximal voluntary contractile force as a result of deficits within the central nervous system, in the neural drive of the muscle, or within the muscle itself (McGuigan, 2017). Meanwhile, supercompensation refers to a return to a level that exceeds the baseline, resulting in an increased performance capacity (Coutts & Cormack, 2014). Assessing fatigue and supercompensation within the neuromuscular system has been referred to as monitoring ‘neuromuscular status’ (Claudino et al., 2016). While there are a variety of options for assessing neuromuscular status in laboratory settings, there are fewer options for monitoring neuromuscular status in sport settings. It has been suggested that jump testing is a suitable assessment of neuromuscular status in sport settings (Taylor et al., 2012). Taylor and company reported that 54% of respondents to a survey on athlete monitoring in high performance sport employ some type of vertical jump test.

There are a variety of tools in which to assess neuromuscular status through jump testing. In its most basic form, jump height can be assessed using a vertical jump apparatus or a tape measure (Joyce & Lewindon, 2014). Meanwhile, many sport settings now have access to technological devices such as force plates, linear position transducers, accelerometers, and contact mats (Taylor et al., 2012). While these devices allow for jump height to be measured, they also allow for the measurement of other jump-derived parameters that may be used to monitor neuromuscular status (Joyce & Lewindon, 2014).

Along with jump height, other jump-derived parameters that may be used by practitioners to monitor neuromuscular status include mean and peak force (eccentric and concentric), mean and peak power (eccentric and concentric), mean and peak velocity (eccentric and concentric), rate of force development, and the ratio of flight time to contraction time (Doeven, Brink, Kosse, & Lemmink, 2018; Taylor et al., 2012). The most employed types of jumps for jump testing include the countermovement jump, static jumps (i.e., no utilization of the stretch-shortening cycle), and drop jumps (McGuigan, 2017; Taylor et al., 2012). Different types of jumps can allow for the utilization of different jump-derived parameters. For example, a Reactive Strength

Index (RSI) is generally determined employing a drop jump testing protocol (Joyce & Lewindon, 2014; McGuigan, 2017).

The countermovement jump (CMJ) has been one of the most utilized tests for monitoring neuromuscular status in individual and team sports (Oliver, Lloyd, & Whitney, 2015; Taylor et al., 2012; Twist & Highton, 2013), as well as in the military (Fortes et al., 2011). Numerous research studies have found CMJ performance to be an objective indicator of neuromuscular fatigue and supercompensation (Claudino et al., 2016; Cormie et al., 2010a,b; Doeven et al., 2018; Gathercole et al., 2015a, b, c; Kennedy & Drake, 2017). In particular, CMJ indices used in the monitoring of neuromuscular status include average and peak jump height, relative power indices, mean and peak power, relative force indices, mean and peak force, peak velocity, rate of force development, eccentric time/concentric time, and flight time/contraction time (Claudino et al., 2016; Doeven et al., 2018; Oliver et al., 2015). The specific selection of which CMJ-derived indices to analyze is dependent upon factors such as the population being monitored, the type, volume, and intensity of the exercise performed, and whether acute or chronic fatigue to suspected (Joyce & Lewindon, 2014; McGuigan, 2017).

When monitoring fatigue in athletes, assessments should represent the functional characteristics of the fatigue-inducing exercise completed (Cairns, Knicker, Thompson, & Sjogaard, 2005). In laboratory settings, fatigue is generally induced and assessed by using isolated muscle actions, which allow for excellent reliability of testing (Gathercole et al., 2015b). However, these findings have limited applicability in applied settings in which athletes engage in dynamic sporting movements involving a variety of muscle groups and utilizing the stretch-shortening cycle (Girard & Millet, 2009; Nicol, Avela, & Komi, 2006).

With the utilization of the stretch-shortening cycle, the CMJ provides a dynamic and athletic movement that replicates the functional characteristics of many sports including American football (Van Hooren & Zolotarjova, 2017). The stretch-shortening cycle of muscle function—characterized by a lengthening phase (eccentric) of muscle action where pre-activation of the muscle occurs subsequently followed by a shortening phase (concentric) muscle action—is utilized during common sporting activities such as running, hopping, jumping, and changing directions (Komi, 2000; Nicol et al., 2006). As noted by Finnish sports science researcher Paavo Komi, "the natural variation of muscle function is more often a stretch and shortening cycle and thus this model provides a good basis from which to study both normal and fatigued muscle" (Komi, 2000, p. 1197).

In addition to monitoring neuromuscular status, monitoring measures of muscular strength and power can provide feedback regarding fatigue and supercompensation. While dynamometry is frequently employed in laboratory settings, strength assessments commonly employed in sport settings include isometric tests and repetition maximum tests (McGuigan, Sheppard, Cormack, & Taylor, 2013). Isometric tests frequently used by practitioners include the isometric mid-thigh pull, isometric squat, and isometric bench press. There has been an increase in the utilization of isometric tests in applied settings due to high reliability, time efficiency, and being less fatiguing and lower risk than maximal strength testing (Comfort et al., 2019). This allows practitioners to more frequently monitor their athletes force and power production capabilities.

Recovery and fatigue

Recovery can be described as a multifaceted (i.e., physiological and psychological) restorative process relative to time (Kellmann et al., 2018). Meanwhile, Halson (2014) describes fatigue as “a complex and multifaceted phenomenon that has a variety of possible mechanisms” (p. S139). When considered together, it is clear that there are many factors influencing the complex relationship between recovery and fatigue. Moreover, practitioners alter training dosages to increase or decrease fatigue based on the training phase and intended outcomes, which adds to the complexity of attempting to monitor fatigue and adjust training loads accordingly (Halson, 2014).

Due to the complexity of their relationship and their multifactorial nature, it has been suggested that recovery and fatigue be viewed on a continuum (Kellmann et al., 2018). Within this recovery—fatigue continuum, the balance between recovery and fatigue is dependent upon such factors as the relative demands of the sport, the phase of the training cycle, and the training status of the athlete (Kellmann et al., 2018). Hence, assessments of fitness characteristics, fatigue, or performance parameters must be viewed relative to the athlete’s position on this continuum (Zatsiorsky & Kraemer, 2006).

There are a variety of definitions of fatigue (Halson, 2014). Broadly, fatigue can be defined as a failure to maintain the required or expected force leading to reduced performance of a given task (Edwards, 1981). However, muscle contraction varies based on the type of stimulus, type of contraction, and type of muscle, as well as the duration, frequency, and intensity of the exercise (Edwards, 1981; Sahlin, 1992). Thus, as noted by Sahlin (1992), “it is therefore evident that the site of fatigue and the factor(s) limiting the exercise will vary and will be dependent on the experimental model and the conditions” (p. 99-100).

In part, the complexity of fatigue is due to the complex nature of a voluntary contraction, which can be described as a cascade of events originating in the cerebral cortex and terminating in the contractile machinery (Enoka, 2008). Hence, fatigue can occur as a result of impairment in one or several stops along the cascade of events from the central nervous system to the contractile apparatus (Enoka, 2008; Sahlin, 1992). As noted by Sahlin (1992), “a distinction is usually made between central fatigue, where the impairment is located in the CNS and peripheral fatigue where the impairment is located in the peripheral nerve or contracting muscle” (p. 100).

Meanwhile, recovery is an umbrella term and can be further characterized by different modalities of recovery such as regeneration or psychological recovery strategies (Kellmann et al., 2018). Kellmann et al. (2018) describe regeneration in sport and exercise as “the physiological aspect of recovery and ideally follows physical fatigue induced by training and competition” (p. 240). Regeneration approaches include strategies such as cold water immersion, massage, nutritional interventions, and sleep (Halson, 2016; Kellmann et al., 2018; Kentta & Hassmen, 1998). In comparison, psychological recovery strategies targeting mental fatigue (i.e., cognitive exhaustion) include psychological interventions such as cognitive self-regulation, resource activation, and relaxation techniques (Kellmann et al., 2018).

Athlete Monitoring: Individual Factors

An individualized approach to athlete monitoring is vital (Gabbett et al., 2017). Establishing a dose-response relationship between training stimuli and their responses is the foundation of athlete monitoring, and the relationship between a particular training dosage and measures of performance are likely influenced by a myriad of individual factors (McGuigan, 2017). Factors such as genetics, age, gender, initial fitness level, training history, and current state of readiness are likely to influence this relationship (Thornton, Delaney, Duthie, & Dascombe, 2019; Windt, Zumbo, Sporer, MacDonald, & Gabbett, 2017). Therefore, it is vital to examine each athlete’s individual response rather than just focusing on group averages.

When monitoring individual athlete data within team sports, relevant changes in variables should be presented not only as within athlete changes, but also in comparison to others within similar groups. This can be done through utilizing statistics such as Z-scores, which allows for individual changes to a given treatment/stimulus to be compared to those changes within the group (Thornton et al., 2019). Thus, the individual response to a given treatment/stimulus can be interpreted relative to the change observed in other individuals.

In addition, the individualization of training stimuli can be accounted for with the use of monitoring technology. Pre-existing measures of physical fitness and performance such as maximal speed, aerobic capacity, anaerobic capacity, resting heart rate, and heart rate variability can be used to prescribe a training stimulus that is individualized based on these qualities (Joyce & Lewindon, 2014; Thornton et al., 2019). For example, integrated microtechnology software allows for the individualized high speed running values based on an athlete's maximal speed, as opposed to absolute speed zones. Similarly, heart rate indices allow for conditioning to target specific energy systems by taking into account an athlete's resting and maximal heart rates (e.g., heart rate reserve method).

Therefore, assessing pre-existing individual characteristics, such as those mentioned above, allow practitioners to better understand specific athlete factors that may modify the effect of a given training stimulus (Joyce & Lewindon, 2014). This allows for a more individualized approach based on an athlete's given 'profile' and ensures they are provided with an appropriate training stimulus based on their individual needs (Thornton et al., 2019).

Athlete Monitoring: Non-Training Parameters

An athlete's responses, and ultimately adaptations, to training stimuli depend not only on what is happening during training and competition, but also on what is happening outside of training and competition (Halson, 2014). Factors such as sleep, nutrition, hydration, wellness, and ‘life load’ (e.g., academics, work, relationships, stress) influence the training response, the fatigue—recovery continuum, and athletic performance (Doeven et al., 2018; Halson, 2014; Mann, Bryant, Johnstone, Ivey, & Sayers, 2016; McLean et al., 2010). Indeed, as noted by McGuigan (2017), “the total stress on the athlete—not just the stress of training and competition—needs to be considered” (p. 4).

For example, Mann and colleagues (2016) found that American football players at the collegiate level were at a greater risk of developing an illness or having a training-related injury during periods of high academic stress. Meanwhile, a lack of sleep has been found that have a negative effect on athlete performance, reduce motivation, increase the perception of effort for a given workload, and impair a variety of other biological functions (Fullagar et al., 2015; Halson, 2014; Mah, Mah, Kezirian, & Dement, 2011). Finally, nutrition has been shown to influence the training response, recovery, and performance (Barr & Heaton, 2015; Casazza, Tovar, Richardson, Cortez, & Davis, 2018; Jeukendrup, 2014; Macnaughton et al., 2016).

Assessment of non-training parameters can provide practitioners with insight into athlete fatigue and readiness (Laurent et al., 2011; McGuigan, 2017). Coutts and Reaburn (2008) used the Recovery-Stress Questionnaire for Athletes (RESTQ-Sport) to monitor changes in perceived stress and recovery during an intensified period of training in rugby league players. The authors found that RESTQ-Sport subscale measures of stress and recovery were associated with the intensified training period, as well as the subsequent taper period. Measures such as fatigue, disturbed breaks, and general stress increased during the intensified training period and decreased during the taper period, while recovery measures such as physical recovery, social relaxation, general well-being, and sleep quality decreased during the intensified training period and increased during the taper period (Coutts & Reaburn, 2008). These findings are similar to those of McLean and colleagues (2010) in their examination of perceptual wellness during different recovery periods between matches in professional rugby players.

Chapter 3

General Methods

The purpose of the general methods section is to describe the participants and procedures, which includes describing the tools being employed in this line of research, the variables being analyzed, and the analytical approaches being used to examine the data. Since the same tools were used across all studies within this line of research, this chapter will provide an overview of these devices. Specific testing procedures, training protocols, and analytical approaches will described within each study's subsection. Additionally, participants from each study were drawn from the same population. Thus, this chapter will describe the population, while specifying the characteristics of each study's participants.

Integrated Microtechnology

The external training load of individuals can be quantified through the use of integrated microtechnology including a global positioning system (GPS), accelerometer, gyroscope, and magnetometer (Halson, 2014). The integrated microtechnology devices employed in this line of research were STATSports Apex Units (STATSports, Northern Ireland) that include an 18 Hz GPS, 600 Hz accelerometer, 400 Hz gyroscope, and a 10 Hz magnetometer. These devices were trunk-mounted and situated on the upper back of the athletes just between the scapulae (Ward, 2018; Wellman et al., 2016, 2017).

Commercially available devices have been shown to be reliable for capturing running-based activities including linear forward running and sprinting, multidirectional activities, and change of directions actions (Beato & de Keijzer, 2019; Coutts & Duffield, 2010; Tessaro & Williams, 2018). Beato and de Keijzer (2019) reported excellent inter-unit reliability with intraclass correlation coefficients of 0.96, 0.95, 0.95, 0.97, and 0.99 when sprinting 5-10 m, 10-

15 m, 15-20 m, 20-30 m, and 5-30 m, respectively. In addition, Johnston et al. (2014) found GPS devices to be accurate when measuring total distance and peak speed.

Participants were provided with an integrated microtechnology unit prior all running based training, field work and drills (e.g., position drills, acceleration and maximal velocity training, metabolic conditioning, etc.), sport practices, and competitions. One unit was assigned per participant for the duration of data collection (Beato & de Keijzer, 2019; Coutts & Duffield, 2010). Units were collected after completion of training, practice, or competition. Subsequent to unit collection, data was downloaded using STATSports Apex software and then exported to Microsoft excel for further analyses and reporting.

Polar H10 heart rate monitors (Polar, United States) were employed in conjunction with the integrated microtechnology. Heart rate straps were provided to participants and were worn around their chest with the heart rate sensor placed on the skin directly over their xyphoid process (DeMartini et al., 2011). Heart rate data were synced to each participant's integrated microtechnology device and heart rate data were downloaded using the STATSports Apex software and then exported to Microsoft excel.

Variables

The selected integrated microtechnology variables included in this line of research were total distance, speed intensity, high metabolic load distance, accelerations and decelerations, impacts, high speed running, explosive distance, dynamic stress load, and total loading. The selection of integrated microtechnology variables were informed by prior investigations into the physical demands of American at both the collegiate (DeMartini et al., 2011; Wellman et al., 2016,2017) and professional levels (Ward, 2018). Meanwhile, heart rate indices included average heart rate and a heart rate exertion score. Thus, there were variables included in this line of research capturing both external and internal load (Bourdon et al., 2017).

Table 3.1 STATSports Metric Definitions

STATSports Metric	Definition
Total Distance (yards)	Total distance covered by player(s) in selected drill/session.
Speed Intensity (AU)	Measure of total exertion based on a convex curve and weightings for each individual speed. The more time spent at higher speeds, the higher the speed intensity score.
High metabolic load distance (W/kg)	Distance covered performing any activity above 25.5 W/kg.
Accelerations (m/s^2)	Accelerations with a minimum duration of 0.5 s.
Decelerations (m/s^2)	Decelerations with a minimum duration of 0.5 s.
High Speed Running (yards)	Distance covered traveling above 80% of positional max speed.
Explosive Distance (HMLD – HSR)	Distance covered while accelerating/decelerating above acceleration threshold (i.e., 4 m/s^2).
Dynamic Stress Load (AU)	Weighted total of impacts above 2G based on convex curved G force ratings.
Impacts (G Force)	The magnitude sum of 3 axis accelerometer values over 1 second period, greater than 2 G.
Total Loading (AU)	Using accelerometer data alone, gives a total of the forces on the player over the entire session without any weightings being applied.
Average Heart Rate (bpm)	Average player heart rate during session/drill.
Heart Rate Exertion (AU)	Log scale of heart rate % following convex curve with each heart rate score getting a specific weighting.

The definitions of the integrated microtechnology metrics used in this line of research are displayed in table 3.1. Of these metrics, acceleration, deceleration, and impact zones were created to display different levels of intensity as their own variables (Wellman et al., 2016, 2017). Descriptions of these zones are displayed in tables 3.2 and 3.3. In combination, these variables were used to describe the external and internal load of American football athletes during practices (DeMartini et al., 2011; Ward, 2018; Wellman et al., 2016, 2017), along with partially quantifying the fatigue-inducing stimulus in study 3 (Halson, 2014).

Table 3.2 Impact Classification Scale

Impact Zone	Gravitational Force
Zone 1	3-5
Zone 2	5-7
Zone 3	7-9
Zone 4	8-10
Zone 5	10-13
Zone 6	13-15

Table 3.3 Acceleration/Deceleration Classification Scale

Acceleration/Deceleration	m/s^2
Zone 1	0.5-1
Zone 2	1-2
Zone 3	1.5-2.5
Zone 4	2.5-3.5
Zone 5	3.5-5
Zone 6	>5

Force Platform Testing System

The force plate testing system utilized in this line of research was a Force Decks FD4000 system (Vald Performance, Australia). The Force Decks FD4000 and FDLite consists of a pair of connected platforms, each with high capacity load cells (one in each corner). When load is applied, the inputs from each transducer are summed to provide an overall left platform and overall right platform output (Beckham, Suchomel, & Mizuguchi, 2014).

A force platform (otherwise known as a force plate) is a device utilized to measure the external forces applied onto the ground by an individual as they perform a movement (Beckham, Suchomel, & Mizuguchi, 2014). The total vertical ground reaction forces for both limbs (as well as single-limbs) are measured, from which acceleration, velocity, and other derivatives are calculated. The measurements captured by a force platform provide a detailed picture of the interaction between an individual and the ground—not just the physical output achieved, but also the technique or strategy utilized to achieve a given physical output.

Numerous researchers have examined the reliability and validity of jump testing protocols as indicators of neuromuscular status (Cormack, Newton, McGuigan, & Doyle, 2008; Cormack, Mooney, Morgan, & McGuigan, 2013; Gathercole et al., 2015a; Gibson, Boyd, & Murray, 2016; Oliver et al., 2015). Jump testing performed on a force platform has been shown to be reliable during both single and repeated countermovement jump testing protocols (Cormack et al., 2008). While both single jumps and repeated jumps have been shown to be reliable, single countermovement jumps have been reported to have a higher degree of reliability (Cormack et al., 2008).

Variables

Variables analyzed from the force platform included jump height, relative mean force, relative mean power, and peak velocity. These variables describe the physical output or performance that was achieved and have been reported as 'typical' variables analyzed during countermovement jump testing (Gathercole et al., 2015a,b,c). Jump output variables displaying the physical output achieved are used as outcome measures in the vast majority of research investigations assessing neuromuscular status (Cormack et al., 2008; Gathercole et al., 2015a, b, c; Kennedy & Drake, 2017; Oliver et al., 2015; Twist & Highton, 2013).

Meanwhile, variables that pertain to how a given physical output or performance was achieved were also analyzed in this line of research. These jump strategy variables included flight time-to-contraction time ratio, reactive strength index modified, eccentric and concentric duration. These variables can be viewed as 'alternative' variables assessed during the countermovement jump (Gathercole et al., 2015b,c). While these variables have been examined to a lesser extent, it has been suggested they may provide a higher sensitivity to neuromuscular fatigue and training related adaptations in elite athletic populations (Gathercole et al., 2015a,b,c; Kennedy & Drake, 2017).

Participants

Participants in this line of research were collegiate American football athletes aged between 18-24 years. Participant characteristics (mean ± standard deviation) for each position group are presented in table 3.4. Participant characteristics include height, body mass, and body fat percentage means and standard deviations for all position groups analyzed. All participants were student-athletes at Virginia Tech and were cleared for athletic participation by the sports medicine department. Ethical approval was provided by the institutional review board and the athletic research review board. Individual consent was obtained from each student-athlete whose data were to be included in this line of research.

All participants were categorized into one of seven positional groups: defensive back (DB), wide receiver (WR), tight end (TE), linebacker (LB), running back (RB), defensive line (DL), or offensive line (OL). All data were collected as part of the athlete monitoring program developed and implemented by the author, as part of his professional duties as the Director of Sports Science/Assistant Director of Strength and Conditioning for Virginia Tech football.

Table 3.4 Participant Characteristics by Position Group

Position	Height (cm)	Body Mass (kg)	Body Fat (%)
Wide Receiver (n = 5)	191.5 ± 2.8	94.5 ± 8.2	8.6 ± 7.0
Tight End (n = 5)	192.8 ± 1.1	102.3 ± 11.1	17.4 ± 8.5
Running Back (n = 5)	183.8 ± 1.2	96 ± 9.2	12.1 ± 6.1
Offensive Line (n = 4)	198.2 ± 0.6	141.8 ± 18.8	27.4 ± 13.9
Defensive Line (n = 5)	192.4 ± 1.5	128.5 ± 16.2	21.9 ± 11.8
Linebacker (n = 5)	190.2 ± 1.1	111.9 ± 12.3	14.9 ± 9.3
Defensive Back (n = 6)	186.7 ± 1.4	87.1 ± 8.6	7.2 ± 4.8

Practice Sessions

The practice week consisted of four scheduled practices and one walkthrough—a walkthrough is a slow paced, non-contact time when coaches review formations and offensive/defensive sets with their players. Practice sessions were divided into pre-practice and practice with both sessions being considered one entire practice period. The pre-practice session consisted of a walkthrough, a stretch period, and a specialty period, while the practice portion consisted of 17-24 five minute periods with different foci. The number of periods per practice was dependent upon the day of the week with each day of the week targeting different tactical, technical, and physical aspects for game preparation.

Practices were coded by the day of the week since each practice had a distinct purpose and set of objectives. Practices on Tuesday and Wednesday generally occurred on the outdoor practice field, while practices on Thursday and Sunday generally occurred in the indoor training facility. When using integrated microtechnology indoors, running-based metrics are generated using a mathematical algorithm via the data generated directly from the accelerometer. For this reason, data were analyzed differently based on whether they were collected indoor or outdoor.

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 26.0. Descriptive statistics were generated for all practices. For Tuesday and Wednesday practices, all metrics described in table 1 were analyzed for daily means and standard deviations. Meanwhile, for Sunday and Thursday practices, only accelerometer-derived data were analyzed due to the uncertainty surrounding the algorithm utilized by STATSports. The accelerometer-derived only data included total loading, dynamic stress load, and impacts, as well as the heart rate indices.

Specific Methods

The specific methods section will describe the statistical procedures employed for each study, as well as each study's specific research procedures. While each study used many of the same variables, there are specific analytical approaches and experimental procedures utilized to address the research objectives put-forth in each study.

Study 1

The purpose of study 1 was to better understand the physical demands of American football through determining the external and internal training loads associated with in-season practices in American collegiate football athletes. In addition, a secondary purpose of this investigation was to explore the relationship between different training load data collected during practice via an integrated microtechnology device and a heart rate monitor. The aim was to find the best subset of metrics that describe athlete training load for collegiate American football athletes.

The external load variables selected for analysis were chosen based on the their representation of the physical movements of American football and the previous investigations into the physical demands of American collegiate football (DeMartini et al., 2011; Wellman et al., 2016; Wellman et al., 2017). Meanwhile, heart rate indices were used to represent the internal response of the athletes to the external load placed on them during practice (Bourdon et al., 2017; DeMartini et al., 2011).

It has been shown that football is a sport consisting primarily of running (e.g., high speed running, sprinting), multi-directional movements (e.g., acceleration, deceleration, backpedaling), and physical collisions (DeMartini et al., 2011; Ward, 2018; Wellman et al., 2016, 2017). Thus, the following external load variables were selected for analysis: maximal speed, total distance, high metabolic load distance, quantity of accelerations/decelerations at different intensity zones, speed intensity, explosive distance, quantity of impacts at different severity zones.

To describe the physical demands of American football, descriptive statistics including measures of central tendency and variability were generated. Differences between position groups were determined by conducting a one-way analysis of variance (ANOVA) and generating group main effects. Statistical significance was set to a p value of <.05. Prior to the one-way ANOVA being conducted, a test for homogeneity was performed, which revealed that the assumption of variance was violated. Thus, a Welch Robust Test of Equality was conducted to determine the main effects between position groups (Ward, 2018). Meanwhile, a Tukey post-hoc analysis was conducted and used to interpret positional differences (Wellman et al., 2016, 2017).

To determine the most appropriate subset of external load variables for monitoring athletes in American collegiate football, a principal components analysis (PCA) was conducted (Ward, 2018). A PCA is a statistical method that seeks to reduce the dimension of a dataset that consists of highly correlated variables down to a subset of key factors, or ‘principal components’, that explain similar constructs (Federolf et al., 2014). Variables within each component can be weighted based on their coefficient, which can then be used to describe each component as a training load construct specific to the sport (Ward, 2018).

For a PCA to be an appropriate statistical method, the data must be highly correlated. For this reason, a Bartlett’s Test of Sphericity was conducted to evaluate the appropriateness of the dataset based on the relationship between external load variables. The test was found to be significant (p <.001), which indicated the correlations between variables were acceptable for conducting the PCA. To assess the sampling adequacy of each variable, a Kaiser-Meyer-Olkin (KMO) test was administered (Clark & Ma’ayan, 2011). The overall KMO score was 0.79 with each variable having an individual score between 0.56-0.93. Based on the minimum criteria established by Kaiser (1974), the results of the KMO test indicate acceptability of the selected variables.

Due to many of the constructs being highly correlated, a direct oblimin rotation was used for the analysis (Costello & Osborne, 2005). The extraction level was set at 1 eigenvalue, which is considered an appropriate level for a PCA with an adequate sample size (i.e., >200 observations; Kaiser, 1974). The pattern matrixes and scree plots were used to interpret components (Costello & Osborne, 2005). Finally, small coefficients <.30 were suppressed, and thus, are not displayed in the matrixes (Burnett et al., 1997).

Study 2

The purpose of study 2 was to examine the effect of a periodized training program on changes in countermovement jump (CMJ) performance over the course of two 4-week summer training blocks (total of 8 training weeks). A secondary purpose of this examination was to determine the efficacy of using the CMJ to monitor longitudinal training adaptations in American collegiate football athletes.

Testing

Five collegiate American football athletes completed CMJ testing every Wednesday prior to their training session that day for 8 consecutive weeks. Participants were familiarized with performing a CMJ prior to the testing period. Prior to each jump, participants completed a standardized warm-up consisting of 10 repetitions of the following: medicine ball slams, banded good mornings, and pojo jumps. A 2 minute rest period will separate the warm-up period from the testing period.

There was a 1 week baseline testing period during which the participants completed three CMJ trials on Monday, Wednesday, and Friday. This one week baseline testing period is prior to training occurring. The baseline testing period allowed for participants to become familiarized with the CMJ, as well as allowed practitioners to determine non-fatigued, baseline measures over the course of 1 week to calculate normal range values including a daily mean, standard deviation, and a coefficient of variation.

Training

The training program consisted of 5 training sessions per week and involved resistance training aimed at developing strength and power (see appendix c for example), as well as field work focused on speed development and conditioning (see appendix d for example), which occurred on alternate days. Primary strength exercises included during the 8 weeks of training are listed in table 3.5. This is not a comprehensive list, but rather a list of all primary exercises prescribed as part of the strength and conditioning program. Other 'secondary' movements include isolation and core movements that are less taxing on the central nervous system.

Table 3.5 Strength Training Exercise Description

Upper Body	Lower Body	Olympic/Olympic Derivatives
Flat Barbell Bench Press	Barbell Back Squat	Snatch Pull
Incline Barbell Bench Press	Barbell Front Squat	Power Clean
Overhead Press	Front-Foot Elevated Split Squat	Hang Power Clean
Barbell Row	Romanian Deadlift (RDL)	Clean Pull
Single-Arm Landmine Row	Single-Leg RDL	Block Pull

All running-based work termed as ‘field work’ consisted of tempo runs, acceleration drills, drills to support the development of max velocity sprinting technique, and change of direction drills. During tempo runs, athletes were instructed to accelerate hard with a positive shin angle for 6-8 yards and then ‘get tall’ to enter max velocity running technique. In addition, they were instructed to be run between 70-80% of their maximal speed. Feedback was provided to the athletes from live stream GPS monitoring. Rest periods were between 60-90 seconds (dependent upon heart rate recovery) and each repetition was between 50-100 yards.

CMJ Variables

The CMJ variables analyzed consisted of both jump output and strategy variables. The jump output variables included jump height, relative mean force, relative mean power, and peak velocity. Meanwhile, the jump strategy variables include flight time-to-contraction time ratio, reactive strength index modified, and concentric and eccentric duration.

Analytical Approach

In order to reduce the skew of mean data, 2 out of the 3 CMJ trials were averaged and used in the analysis (Gathercole et al., 2015b). Univariate analyses were conducted on each CMJ variable to determine the between subjects effects with the significance level set at $p < .001$. The CMJ variable measurement was the dependent variable, while time was the fixed factor and subject ID was the random factor (Howell, 2013). Partial eta squares were reported and interpreted as the proportion of variance in the dependent variable explained due to the effect of time (Twist & Highton, 2013).

A Tukey post-hoc analysis was conducted to make multiple comparisons between each point in time for each CMJ variable (Cormie et al., 2010a,b). In addition, this allowed for the mean differences between subjects at different points in time to be analyzed for statistical significance (Howell, 2013). Trends in the effect of the training program on CMJ performance were interpreted using the Tukey post-hoc analysis (Cormie et al, 2010a,b).

Study 3

The purpose of this study was to examine the effect of acute fatigue on countermovement jump (CMJ) performance in American collegiate football athletes. A secondary purpose of this study was to determine the efficacy of the CMJ test for assessing neuromuscular fatigue in American collegiate football athletes.

Testing

Five collegiate American football athletes participated in this study. Each participant was tested prior to (baseline), and immediately after the training session (0 hours), as well as 24 hours post-training. Participants were familiarized with performing a countermovement jump prior to testing. Prior to each jump, participants completed a standardized warm-up consisting of ten repetitions of the following: medicine ball slams, banded good mornings, and pojo jumps. A 2 minute rest period separated the warm-up period from the testing period.

The fatigue-inducing protocol consisted of a strength training session comprising movements targeting the upper body. The strength training portion of the session last approximately ~45 minutes and was immediately followed by a dynamic warm-up period (~15 minutes—see appendix e), and a running protocol consisting of cone drills and shuttle runs. A description of the strength training portion of the training session is presented in table 3.6. The external training load of the running protocol represented one of the highest volumes of high speed running and high metabolic load distance (HMLD) completed during summer training. The description of the external training load is presented in table 3.7.

Table 3.6 Strength Training Protocol

Exercise	Sets x Repetitions

Snatch Pulls	4 x 3
Bench Press	5 x 3
Pendlay Row	4 x 5
TRX (Y, W, Face Pull)	3 x 12
Lateral Neck Hold	3 x 10 seconds
Banded Triceps Extensions	3 x 25

Table 3.7 Description of Training Load

Training Load Metric	Mean	Standard Deviation
Total Distance (yards)	3431.2	761.8
High Speed Running	808.1	107.3
HML Distance	1091.6	160.1
Explosive Distance	282.8	103.9
Speed Intensity	338.4	81.2
Dynamic Stress Load	118.7	67.3
Total Loading	82.4	54.2
Average Heart Rate	144.3	12.4
Heart Rate Exertion	398.2	91.2

CMJ Variables

The CMJ variables analyzed consisted of both jump output strategy variables (Gathercole et al., 2015b,c). The jump output variables included jump height, relative mean force, relative mean power, and peak velocity. Meanwhile, the jump strategy variables included flight time-to-contraction time ratio, reactive strength index modified, concentric duration, and eccentric duration.

Analytical Approach

In order to reduce the skew of mean data, 3 out of the 4 CMJ trials were averaged and used in the analysis (Gathercole, Sporer, Stellingwerff, & Sleivert, 2015). To determine the differences that occurred, the magnitude of change was determined via an effect size calculation (Gathercole et al., 2015b,c; Kennedy & Drake, 2017). Each individual time point (0 hours and 24 hours post-training) was compared to the pre-training (baseline) measures. Group effect sizes were calculated based on interindividual variability (i.e., typical error; Gathercole et al., 2015b).

The typical error from the pretest sessions were utilized. Effect size inferences were made using the following thresholds: <0.3 small, <0.9 moderate, <1.6 large, and >1.6 very large (Twist & Highton, 2013).

Differences between groups due to the effect of time was determined by conducting a univariate analysis on each CMJ variable. The CMJ variable was the dependent variable, while time was the fixed factor and subject ID was the random factor. A test of between-subjects effects was used to determine if there was a significant difference at the $p < .001$ level between groups due to the effect of time (Gathercole et al., 2015b). A Tukey post-hoc analysis was used to make multiple comparisons between different points in time. Significant differences between points in time were marked accordingly.

Chapter 4

Results

The purpose of this chapter is to display the analytical results, while providing a separate and specific discussion for each study based on the findings. The discussions provided within this chapter focus on situating the findings within the research literature, while the general discussion in chapter 5 will focus on practical application.

Study 1

Principal Component Analysis

In the examination of all metrics from outdoor practices, subject data (n = 35) for outdoor practices on Tuesdays and Wednesdays (18 sessions) were included in the analysis (496 observations). The descriptive statistics are displayed in table 4.1. Group means and standard deviations for each metric included in the analysis of outdoor practices on Tuesday and Wednesday is outlined in table 4.1.

Table 4.1 Descriptive Statistics – Tuesday and Wednesday Practices

Training Load Variable	Mean	Std. Deviation	Analysis N
External Load			
Max Speed	16.29	3.76	496
Distance Total	4521.01	1342.25	496
Dynamic Stress Load	104.91	57.53	496
Total Loading	63.05	14.53	496
High Speed Running	128.35	176.71	496
Speed Intensity	188.74	60.09	496
HML Distance	379.28	331.23	496
Explosive Distance	250.92	183.11	496
Accelerations Zone 1	269.98	123.75	496
Accelerations Zone 2	107.98	33.57	496
Accelerations Zone 3	78.32	30.52	496
Accelerations Zone 4	41.00	25.21	496
Accelerations Zone 5	30.34	18.43	496
Accelerations Zone 6	12.10	12.80	496
Decelerations Zone 1	333.53	154.59	496

Decelerations Zone 2	133.38	46.71	496
Decelerations Zone 3	68.53	30.98	496
Decelerations Zone 4	29.28	22.39	496
Decelerations Zone 5	18.29	22.10	496
Decelerations Zone6	6.97	9.51	496
Impacts Zone 1	1137.96	465.00	496
Impacts Zone 2	707.81	347.02	496
Impacts Zone 3	158.53	119.57	496
Impacts Zone 4	36.50	41.26	496
Impacts Zone 5	8.62	12.99	496
Impacts Zone 6	6.02	6.42	496
Internal Load			
Average Heart Rate	115.00	17.11	496
Heart Rate Exertion	160.70	85.21	496

Based on the pattern matrix displayed in table 4.2, there were 6 components with eigenvalues over 1 that explained 85.15% of the variance. Meanwhile, the first 5 components explained approximately 81% of the variance, while also having large coefficients. When interpreting a pattern matrix for the identification of 'principal' components, a graphical representation of the components in terms of eigenvalues can assist in identifying leveling off points at which there is a distinctive change in the slope of the data (Federolf et al., 2014). The scree plot in figure 4.1 shows the eigenvalues plotted against all components, which allows for an analysis of the number of components needed to explain the variance based on the slope of the curve. When examining figure 4.1, there is distinct leveling off at the elbow of the slope between components 5 and 6.

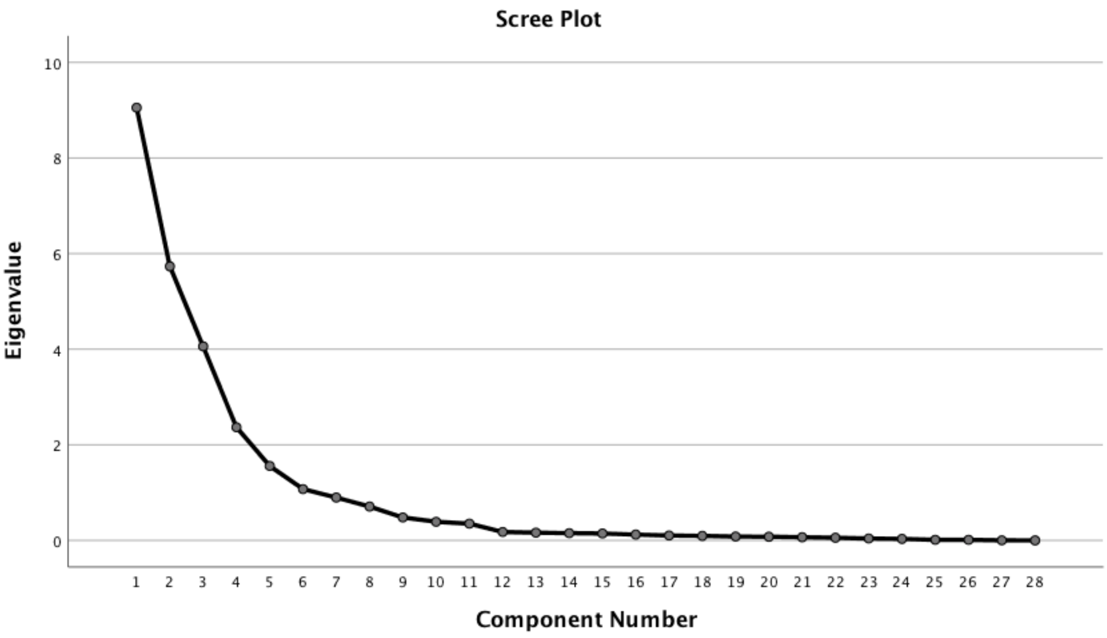
Table 4.2 Pattern Matrix – Tuesday and Wednesday Practices

Training Load Variable	**Components**					
	1	2	3	4	5	6
Max Speed		.742				
Distance Total		.654		.387		
Dynamic Stress Load			.936			

Total Loading			.476			.472
High Speed Running		.915				
Speed Intensity		.671		.301		
HML Distance		.907				
Explosive Distance		.757				
Accelerations Zone 1				.913		
Accelerations Zone 2				.909		
Accelerations Zone 3	.827					
Accelerations Zone 4	.900					
Accelerations Zone 5	.787					
Accelerations Zone 6	.588	.647				
Decelerations Zone 1				.924		
Decelerations Zone 2				.868		
Decelerations Zone 3	.822					
Decelerations Zone 4	.910					
Decelerations Zone 5	.906					
Decelerations Zone 6	.874					
Impacts Zone 1		.477				.584
Impacts Zone 2			.641			.395
Impacts Zone 3			.934			
Impacts Zone 4			.959			
Impacts Zone 5			.923			
Impacts Zone 6			.750			
Average Heart Rate					.946	
Heart Rate Exertion					.966	

The scree plot in figure 4.1 shows the eigenvalues plotted against all components, which allows for an analysis of the number of components needed to explain the variance based on the slope of the curve. When examining figure 4.1, there is distinct leveling off at the elbow of the slope between components 5 and 6. Thus, the first 5 components may be considered ‘principal’ components in terms of the minimal subset of components that explain most of the variance within the dataset.

Figure 4.1 Scree Plot – Tuesday and Wednesday Practices



In the examination of data from the accelerometer-derived only metrics, subject data for practices on Thursdays and Sundays were included in the analysis (481 observations). The descriptive statistics are displayed in table 4.3. Group means and standard deviations for each metric included in the analysis of accelerometer-derived only metrics from practices on Sundays and Thursdays is outlined in table 4.3.

Table 4.3 Descriptive Statistics – Sunday and Thursday Practices

Training Load Variable	Mean	Std. Deviation	Analysis N
Dynamic Stress Load	98.22	57.74	481
Total Loading	55.72	17.01	481
Average Heart Rate	113.37	15.59	481
Heart Rate Exertion	123.62	82.23	481
Impacts Zone 1	923.07	474.58	481
Impacts Zone 2	647.59	346.16	481
Impacts Zone 3	159.60	122.45	481
Impacts Zone 4	36.93	43.08	481

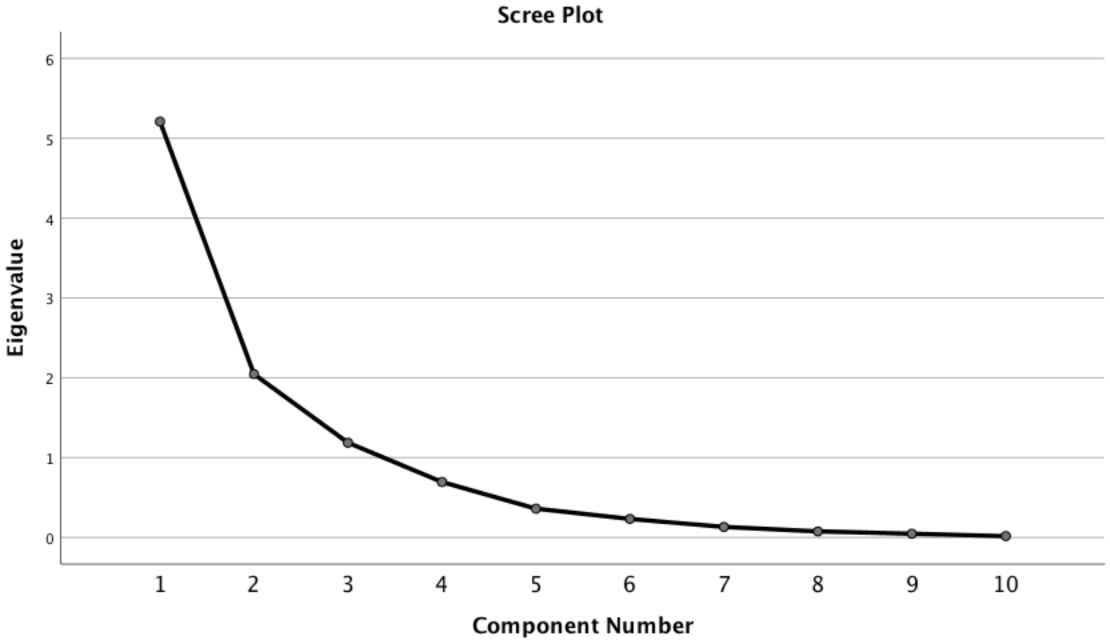
Impacts Zone 5	8.79	13.67	481
Impacts Zone 6	5.56	5.82	481

Table 4.4 Pattern Matrix – Sunday and Thursday Practices

Training Load Variable	Components		
	1	2	3
Dynamic Stress Load	.875		
Total Loading		.794	
Average Heart Rate			.946
Heart Rate Exertion			.855
Impacts Zone 1		.887	
Impacts Zone 2	.446	.643	
Impacts Zone 3	.872		
Impacts Zone 4	.969		
Impacts Zone 5	.946		
Impacts Zone 6	.768		

Based on the pattern matrix displayed in table 4.4, there were 3 components with eigenvalues over 1 that explained 84.40% of the variance. The scree plot in figure 4.2 shows the eigenvalues plotted against all components, which allows for an analysis of the number of components needed to explain the variance based on the slope of the curve. The leveling off in the slope in figure 4.2 occurs after component 3.

Figure 4.2 Scree Plot – Sunday and Thursday Practices



Descriptive Analysis – Sunday and Thursday Practices

Tables 4.5 and 4.6 display descriptive statistics for accelerometer-derived only metrics including dynamic stress, total loading, impacts, along with heart rate indices such as average heart rate and heart rate exertion. Descriptive data are displayed by position group and include means and standard deviations. Table 4.5 provides offensive positional profiles, while table 4.6 provides defensive positional profiles.

Table 4.5 Offensive Profiles – Sunday and Thursday Practices

Training Load Variables	Wide Receiver (WR)	Running Back (RB)	Tight End (TE)	Offensive Line (OL)
External Load				
Dynamic Stress Load	129.9 ± 81.2	73.5 ± 31.2	108.92 ± 37.1	62.5 ± 37.6
Total Loading	58.2 ± 20.9	46.5 ± 15.3	54.2 ± 14.3	40.1 ± 13.4
Impacts Zone 1	877.3 ± 340.3	743.7 ± 332.1	730.2 ± 253.3	399.6 ± 132.0
Impacts Zone 2	918.3 ± 461.8	653.8 ± 239.0	798.7.0 ± 299.1	433.5 ± 213.5
Impacts Zone 3	204.5 ± 146.7	112.1 ± 80.3	231.4 ± 89.1	140.6 ± 111.7
Impacts Zone 4	46.8 ± 46.3	22.2 ± 25.6	44.5 ± 22.3	23.4 ± 20.9
Impacts Zone 5	10.8 ± 13.7	4.38 ± 7.0	9.69 ± 6.7	4.2 ± 3.5

Impacts Zone 6	5.93 ± 5.2	3.73 ± 2.8	5.1 ± 3.3	4.7 ± 3.9
Internal Load				
Average Heart Rate	112.4 ± 18.7	113.1 ± 14.7	116.8 ± 10.7	111.4 ± 11.7
Heart Rate Exertion	85.7 ± 60.0	97.1 ± 65.6	97.9 ± 41.0	80.9 ± 35.8

Significant ($p <.001$) main effects from ANOVA testing were found for the following movement profile variables examined in the analysis of Sunday and Thursday practices: dynamic stress load, total loading, impact zones 5 and 6, and heart rate exertion. A Tukey post-hoc analysis found significant differences ($p <.001$) in dynamic stress load based on position group. Wide receiver, tight end, and linebacker dynamic stress load was significantly higher than defensive back, running back, defensive linemen, or offensive linemen dynamic stress load, while defensive linemen dynamic stress load was significantly higher than offensive lineman dynamic stress load. There were no significant differences between running back and defensive back in terms of dynamic stress load.

Wide receivers, tight ends, and linebackers had a significantly higher total loading value than running backs and offensive linemen. Meanwhile, defensive linemen had a significantly higher total loading value than offensive linemen. Wide receivers, tight ends, and defensive linemen had significantly more zone 5 impacts than all other position groups. However, there were no statistically significant differences in zone 5 impacts between wide receivers, tight ends, and defensive backs. Meanwhile, linebackers had significantly more zone 6 impacts than all other position groups.

Linebackers had a significantly higher heart rate exertion score than all other position groups, while running backs, defensive backs and tight ends had significantly higher heart rate exertion scores than wide receiver and offensive linemen. Meanwhile, there were no statistical differences in average heart rate by position group.

Table 4.6 Defensive Profiles – Sunday and Thursday Practices

Training Load Variables	Defensive Back (DB)	Linebacker (LB)	Defensive Line (DL)
External Load			
Dynamic Stress Load	78.4 ± 39.2	139.9 ± 77.4	93.17 ± 54.1
Total Loading	51.8 ± 16.0	58.0 ± 17.3	50.3 ± 13.0
Impacts Zone 1	1213.5 ± 519.4	709.0 ± 259.5	641.2 ± 272.7
Impacts Zone 2	339.2 ± 193.7	791.1 ± 286.3	571.2 ± 181.4
Impacts Zone 3	70.9 ± 51.1	260.7 ± 128.8	159.8 ± 106.1
Impacts Zone 4	15.1 ± 13.1	68.5 ± 52.7	46.0 ± 60.6
Impacts Zone 5	3.5 ± 3.4	19.9 ± 21.3	10.7 ± 18.0
Impacts Zone 6	3.4 ± 2.9	10.3 ± 10.2	6.1 ± 5.9
Internal Load			
Average Heart Rate	109.7 ± 17.8	119.0 ± 14.1	110.1 ± 10.8
Heart Rate Exertion	107.7 ± 85.2	142.4 ± 90.0	99.1 ± 58.3

Descriptive Analysis – Tuesday and Wednesday Practices

Tables 4.7 and 4.8 display descriptive statistics for all analyzed metrics for Tuesday and Wednesday practices. Metrics included in the analysis are max speed, high speed running, high metabolic load distance, total distance, explosive distance, speed intensity, accelerations, and decelerations, as well as accelerometer-derived only metrics including dynamic stress, total loading, and impacts. Heart rate indices such as average heart rate and heart rate exertion were included, as well. Descriptive data are displayed by position group and include means and standard deviations. Table 4.7 provides offensive positional profiles, while table 4.8 provides defensive positional profiles.

Table 4.7 Offensive Profiles – Tuesday and Wednesday Practices

Training Load Variables	Wide Receiver (WR)	Running Back (RB)	Tight End (TE)	Offensive Line (OL)

External Load				
Max Speed (mph)	17.9 ± 3.4	16.4 ± 3.0	16.5 ± 3.8	13.0 ± 3.4
Total Distance (yards)	5497.5 ± 1707.6	4651.3 ± 1460.2	4844.1 ± 1519.1	4015.6 ± 978.7
Dynamic Stress Load (AU)	111.4 ± 54.3	81.2 ± 27.5	116.3 ± 39.1	79.1 ± 37.8
Total Loading (AU)	70.0 ± 15.2	62.4 ± 11.5	73.2 ± 12.5	56.2 ± 10.1
High Speed Running (yards)	326.4 ± 258.3	214.8 ± 212.2	123.3 ± 120.7	12.1 ± 29.0
Speed Intensity (AU)	238.2 ± 78.6	199.4 ± 65.9	203.9 ± 67.4	160.5 ± 38.8
HML Distance (yards)	643.1 ± 460.9	528.3 ± 402.6	434.9 ± 358.0	120.2 ± 86.2
Explosive Distance (yards)	316.6 ± 219.0	313.5 ± 214.0	311.6 ± 251.1	108.1 ± 76.1
Accelerations Zone 1	253.0 ± 101.5	236.0 ± 125.2	295.3 ± 121.3	323.0 ± 133.8
Accelerations Zone 2	111.2 ± 29.2	97.4 ± 25.4	120.2 ± 33.1	129.8 ± 36.3
Accelerations Zone 3	85.8 ± 36.1	73.9 ± 26.8	83.7 ± 26.6	88.6 ± 25.5
Accelerations Zone 4	39.2 ± 28.2	36.8 ± 23.3	42.7 ± 22.3	50.4 ± 26.5
Accelerations Zone 5	32.6 ± 21.0	31.3 ± 19.5	38.8 ± 25.3	22.4 ± 14.8
Accelerations Zone 6	24.3 ± 16.6	12.7 ± 11.3	13.7 ± 11.1	5.1 ± 10.7
Decelerations Zone 1	315.9 ± 141.4	303.7 ± 155.0	377.4 ± 170.3	406.4 ± 175.8
Decelerations Zone 2	127.5 ± 41.9	111.4 ± 32.2	148.4 ± 53.8	155.3 ± 51.0
Decelerations Zone 3	82.9 ± 39.4	63.9 ± 24.7	82.2 ± 35.9	80.8 ± 26.5
Decelerations Zone 4	38.1 ± 25.6	32.4 ± 21.8	32.5 ± 23.9	27.0 ± 19.1
Decelerations Zone 5	24.8 ± 23.1	21.4 ± 24.7	20.8 ± 21.2	14.1 ± 18.3
Decelerations Zone 6	10.3 ± 9.8	5.8 ± 9.1	7.4 ± 9.4	4.3 ± 8.6
Impacts Zone 1	1466.8 ± 4141.2	1358.9 ± 382.1	1110.3 ± 273.2	580.7 ± 161.3
Impacts Zone 2	907.4 ± 366.8	736.4 ± 73.0	1098.4 ± 266.1	512.7 ± 269.3
Impacts Zone 3	168.2 ± 102.7	107.1 ± 80.3	231.4 ± 86.1	141.6 ± 95.7

Impacts Zone 4	38.8 ± 37.3	21.2 ± 15.6	46.5 ± 22.3	23.4 ± 17.9
Impacts Zone 5	8.81 ± 12.7	3.38 ± 7.0	9.69 ± 4.7	4.2 ± 3.5
Impacts Zone 6	5.2 ± 5.2	3.73 ± 2.8	5.1 ± 3.3	4.7 ± 3.9
Internal Load				
Average Heart Rate	112.4 ± 16.9	116.7 ± 16.3	115.3 ± 16.8	119.6 ± 14.9
Heart Rate Exertion	147.8 ± 86.1	177.0 ± 73.5	176.2 ± 80.9	193.2 ± 92.2

Significant (p <.001) main effects from ANOVA testing were found for most all movement profile variables examined in the analysis for Tuesday and Wednesday practices, with the exception of zone 4 accelerations and zones 5 and 6 decelerations. A Tukey post-hoc analysis found significant differences (p <.001) in max speed based on position group. Wide receiver and defensive back max speed was significantly higher than defensive or offensive lineman max speed, while tight end, linebacker, and running back max speed was significantly higher than offensive lineman max speed. There was no significant difference between offensive and defensive lineman in terms of max speed.

A significant difference (p <.001) in total distance was reported by position group. Wide receivers, defensive backs, linebackers, and running backs had significantly more total distance yardage than defensive or offensive linemen. Meanwhile, there was no difference in total distance between defensive and offensive linemen. Significant differences were reported in dynamic stress load. Wide receivers had significantly higher dynamic stress loads than defensive backs, running backs, offensive linemen, or defensive linemen. Meanwhile, linebackers backs had significantly higher measures of dynamic stress load than all other position groups except for tight end.

Wide receivers had significantly higher total loading values than defensive backs, offensive and defensive linemen. Meanwhile, defensive backs and running backs had significantly higher total loading values than offensive and defensive linemen, but there were no significant differences in total loading between defensive backs and running backs, or defensive backs and linebackers. In terms of high speed running, wide receivers had significantly more high speed running yards than all other position groups, while defensive backs, tight ends, linebackers, and running backs had significantly more high speed running yards than either defensive or offensive linemen. Moreover, running backs had significantly more high speed running yards than linebackers or tight ends.

It was found that wide receivers had significantly higher speed intensity values than defensive backs, linebackers, and offensive and defensive linemen. Meanwhile, tight ends and running backs had significantly higher speed intensity values than both offensive and defensive linemen. There were no significant differences in speed intensity between offensive and defensive linemen, or running backs and linebackers.

Wide receivers accumulated significantly more high metabolic load yardage than defensive backs, linebackers, and offensive and defensive linemen. Indeed, offensive and defensive linemen had significantly fewer high metabolic load yards than all other position groups, while defensive linemen had significantly more high metabolic load yards than offensive linemen. There were no other statistically significant differences in high metabolic load yards between position groups. Similarly, all position groups had significantly higher explosive distance values than offensive linemen, however there were no other statistically significant differences among position groups.

There were no statistically significant differences in low-to-moderate intensity accelerations zones 1-4 by position groups. However, wide receivers, running backs, and tight ends had significantly more accelerations in zone 5 than offensive linemen. Meanwhile, wide receivers had significantly more high intensity zone 6 accelerations than all other offensive position groups. In terms of decelerations, wide receivers had significantly more zone 6 decelerations than offensive linemen. There were no other significant differences in deceleration efforts by position groups.

Table 4.8 Defensive Profiles – Tuesday and Wednesday Practices

Training Load Variables	Defensive Back (DB)	Linebacker (LB)	Defensive Line (DL)
External Load			
Max Speed (mph)	17.8 ± 3.5	16.4 ± 3.3	14.7 ± 3.4
Total Distance (yards)	4482.1 ± 1101.4	4406.3 ± 1055.6	3891.4 ± 775.3
Dynamic Stress Load (AU)	88.0 ± 42.6	164.2 ± 87.2	95.7 ± 45.3
Total Loading (AU)	59.5 ± 14.5	67.2 ± 16.3	57.5 ± 11.3
High Speed Running (yards)	128.5 ± 110.1	67.8 ± 76.9	25.8 ± 54.3
Speed Intensity (AU)	187.6 ± 48.9	180.7 ± 43.2	157.8 ± 30.1
HML Distance (yards)	394.5 ± 238.7	352.3 ± 197.8	198.3 ± 119.6
Explosive Distance (yards)	266.0 ± 149.8	284.5 ± 159.7	172.3 ± 95.3
Accelerations Zone 1	235.0 ± 98.4	270.0 ± 98.8	300.6 ± 155.8
Accelerations Zone 2	95.4 ± 25.2	101.4 ± 30.1	111.4 ± 40.1
Accelerations Zone 3	78.7 ± 32.9	72.6 ± 31.2	69.0 ± 24.5
Accelerations Zone 4	43.3 ± 25.7	42.3 ± 24.2	34.6 ± 22.9
Accelerations Zone 5	26.3 ± 15.3	30.8 ± 14.1	32.9 ± 16.9
Accelerations Zone 6	10.1 ± 9.8	13.7 ± 11.1	9.9 ± 10.7
Decelerations Zone 1	284.8 ± 115.4	319.1 ± 117.9	366.9 ± 179.3
Decelerations Zone 2	141.5 ± 44.7	114.0 ± 36.3	134.4 ± 49.7

Decelerations Zone 3	50.6 ± 24.2	68.8 ± 25.9	65.4 ± 24.5
Decelerations Zone 4	26.1 ± 22.4	30.8 ± 19.5	22.2 ± 20.1
Decelerations Zone 5	13.6 ± 18.5	20.9 ± 22.5	15.6 ± 24.1
Decelerations Zone 6	7.7 ± 9.8	6.0 ± 8.6	6.0 ± 9.5
Impacts Zone 1	1516.1 ± 402.2	868.1 ± 220.2	792.3 ± 242.1
Impacts Zone 2	366.5 ± 205.3	925.6 ± 285.6	650.4 ± 158.7
Impacts Zone 3	72.3 ± 49.2	294.3 ± 143.6	158.8 ± 115.3
Impacts Zone 4	16.0 ± 14.5	80.6 ± 61.5	40.5 ± 48.9
Impacts Zone 5	3.5 ± 3.5	23.5 ± 24.4	8.5 ± 10.7
Impacts Zone 6	3.6 ± 3.1	12.8 ± 11.7	6.6 ± 4.8
Internal Load			
Average Heart Rate	111.6 ± 21.3	121.4 ± 16.9	112.6 ± 11.2
Heart Rate Exertion	146.5 ± 91.1	186.7 ± 93.5	130.7 ± 56.7

In terms of impacts, wide receivers had significantly more zone 1 impacts than all other offensive position groups, as well as defensive linemen and linebackers. There were no statistically significant differences in zone 1 impacts between wide receivers and defensive backs. Meanwhile, tight ends had significantly more zone 2 and zone 3 impacts than all other offensive position groups, while linebackers had significantly more zone 2, zone 3, and zone 4 impacts than all other defensive position groups; there were no statistical differences in zone 2 or zone 3 impacts between tight ends and linebackers. Wide receivers and tight ends had significantly more zone 4 and zone 5 impacts than offensive linemen and running backs, while linebackers had significantly more zone 5 and zone 6 impacts than defensive backs or defensive linemen. There were no statistically significant differences in zone 6 impacts between offensive position groups.

Internally, offensive linemen had a significantly higher average heart rate than wide receivers and significantly higher heart rate exertion score than all other offensive players for Tuesday and Wednesday practices. In addition, running backs and tight ends had a significantly higher heart rate exertion score than wide receivers. Defensively, linebackers had a significantly higher average heart rate and heart rate exertion score than either defensive backs or defensive linemen, while defensive backs had a significantly higher heart rate exertion score than defensive linemen for Tuesday and Wednesday practices.

Discussion

This study examined the physiological movement demands of American collegiate football players during in-season practice through the use of integrated microtechnology and heart rate monitors. In addition, this study assessed the influence of playing position on the physiological movement demands of American collegiate football players during in-season practice. Finally, this study examined the numerous metrics generated by an integrated microtechnology instrument to determine the most appropriate subset of metrics to monitor during American collegiate football in-season practices.

Similar to the findings reported by Wellman et al. (2016), player position influenced the physiological movement demands of American collegiate football players. While Wellman and colleagues examined game data, this study examined in-season practices. In this analysis, wide receivers covered significantly more total distance than all other position groups (offense and defense), while also having significantly more high speed running yards than all other position groups. This is similar to game analyses reporting that wide receivers covers more total yardage, while also accumulating more sprints and yards at higher speeds (Wellman et al., 2016).

However, wide receivers did not have a significantly higher speed intensity value or significantly more high metabolic load yards than tight ends (when compared to other offensive players). Based on how these metrics are calculated, this could indicate that although wide receivers spend more time running at high speeds (80%+ max speed) tight ends may accumulate more yardage at moderate speeds (70-80%). This could be due to wide receivers running longer routes linearly, while tight ends many times run shorter routes with distances that do not allow enough time to achieve 80% or greater of their max speed.

In their analysis of game data, Wellman et al. (2016) reported that wide receivers not only accumulated more high speed yardage than all other offensive positions, but also accumulated more moderate speed yardage (10-16 km/hr.). Thus, the findings of this study could be attributed to differences in the style of play (e.g., a spread offense versus a balanced, pro-style offense), or indicate differences in practice versus game demands. Similarly, Wellman and colleagues found that wide receivers had significantly more maximal acceleration and deceleration efforts (>3.5 m/s) than all other offensive position groups. However, in this analysis, there were no statistical differences between wide receivers, tight ends, and running backs in high intensity acceleration or deceleration efforts.

Consistent with the reports from Wellman et al. (2016), defensive backs and linebackers had significantly more high speed running yards than defensive linemen. However, there were no statistically significant differences in high intensity acceleration and deceleration efforts, as those found by Wellman and colleagues. This could indicate differences in practice versus game demands in American collegiate football. During the practice week, the defense prepares for the upcoming game in lower intensity drills allowing for coaches to install and teach the tactical plan for that week’s game. Meanwhile, during the game, defensive players simply play at game speed and there is no teaching or install element.

In this analysis, wide receivers had significantly more zone 1 impacts (3-5 Gs) than all other offensive position groups and most defensive position groups (excluding defensive backs). However, tight ends had more zone 2 (5-7 Gs) and zone 3 (7-9 Gs) impacts than all other offensive position groups. This is in contrast to the findings of Wellman et al. (2017). In their report of impact profiles from game data, Wellman and colleagues reported that wide receivers sustained more “very light” (5-6 Gs) and “light to moderate” (6.1-6.5 Gs) impacts than all other offensive position groups. Since impacts are derived from the trunk-mounted accelerometer through 3 axes of motion, the amount of running heavily influences impact numbers. Thus, it could be theorized that during games in a more balanced offense wide receivers have considerably more light, moderate, and high speed running than other offensive position groups, which greatly influences impact data from the accelerometer.

Meanwhile, it could be theorized that during practice there is naturally less differences in light, moderate, and high speed running between offensive position groups than during games, and thus, less of a pronounced impact on accelerometer data. Furthermore, it could be hypothesized that spread offenses utilize tight ends more like a hybrid wide receiver and running back, which provides them with running yardage more in comparison to a wide receiver and contact/collision more closely resembling a running back. Hence, their impact profiles could be pronounced due to more running requirements and similar blocking requirements when compared to a tight end from a more balanced offensive system.

Similarly to Wellman et al. (2017), it was found in this study that wide receivers sustained more zone 4 (8-10 Gs) impacts than other offensive position groups (“very heavy” impact classification in Wellman et al., 2017). However, in this analysis, it was also found that tight ends also sustained more zone 4 impacts than other offensive position groups with no statistical difference between wide receivers and tight ends.

Meanwhile, Wellman et al. (2017) reported that defensive backs sustained significantly more very light impacts than all other defensive position groups, while defensive tackles and defensive ends sustained more “heavy” and “very heavy” impacts than either defensive backs or linebackers. In contrast, this analysis revealed that linebackers sustained more zone 4 (8-10 Gs) and zone 5 (10-13 Gs) impacts than all other defensive position groups. This finding could be due to differences between practice and game collision and contact. The differences in higher magnitude impacts could be due to the pronounced differences in high speed running between linebackers and defensive linemen during practice. Thus, the impact profile of the linebackers could be drastically influenced by high speed running and high intensity change of direction efforts. Meanwhile, during a game, defensive linemen are physically engaged in numerous collisions on nearly every play, while also accumulating more sprints and high intensity change of direction efforts on average (Wellman et al., 2016, 2017).

The analysis of heart rate data revealed that offensive linemen had a higher average heart rate and a higher average heart rate exertion score during Tuesday and Wednesday practices than other offensive position groups. This finding is in contrast to those reported by DeMartini et al. (2011). In the only other study to examine heart rate indices in American collegiate football players, DeMartini and colleagues reported that non-linemen had a higher maximal heart rate than linemen during 1 practice of the first week of preseason camp with no statistically significant differences in average heart rate. While these findings are in contrast, it is difficult to compare practice during the first week of preseason camp with a sampling of approximately 30 in-season practices over the course of the in-season period. The physical demands of the first week of preseason camp are focused on running-based activities that are (in theory) supposed to prepare athletes for the physiological demands of the rest of preseason camp and the in-season period.

DeMartini et al. (2011) noted that it was expected that non-linemen would have a significantly higher average heart rate due to having a significantly higher maximal heart rate, however this was not the case. The authors hypothesized that this could be due to non-linemen spending more time running and jogging, while spending less time standing and walking. As noted by the authors, “linemen likely engaged in more anaerobic work compared with non-linemen…therefore, it may be true that heart rate average during the active portion of the drills may actually be greater in linemen vs. that in non-linemen” (DeMartini, et al., 2011, p. 2942). Indeed, this may explain the heart rate findings from this analysis.

The novel finding from this analysis is that heart rate exertion could be an indicator of the internal stress placed on linemen during practices that are ‘short field’ where more contact occurs and running-based activities tend to be in smaller areas and covering smaller distances. Early week practices on Tuesday and Wednesday consist of practice periods more closely replicating game demands for linemen (e.g., blocking in full pads, tackling). When paired with larger body sizes and intense engagement for the entire duration on each play (as opposed to those playing outside of the box), it seems appropriate that linemen would have a higher average heart rate and a higher heart rate exertion (or internal load) during these types of practices.

Furthermore, when analyzing data from Sunday and Thursday practices, the significantly higher average heart rate and heart rate exertion score for the offensive linemen dissipated. Indeed, defensive backs and tight ends both had significantly higher heart rate exertion scores than linemen. Since Sunday and Thursday practice consist of no contact, while being in helmets and shorts, they are the practice days that are least similar to the actual sport of American football. Moreover, Sunday and Thursday practices consist of periods involving larger field concepts and football-specific drills.

The PCA analyses provided sets of factors representing distinct constructs for athlete monitoring use during both indoor and outdoor practices in American collegiate football. When examining the outdoor data from practices occurring on Tuesdays and Wednesdays, there were 5 components that explained approximately 81% of the variance and appeared to be the principal components within these data. These 5 components can be described as representing 4 distinct training load constructs within the sport: high intensity change of direction based loading, linear running based loading, whole body mechanical loading, low intensity change of direction based loading, and internal loading.

Principal component 1 consisted of moderate-to-high and high intensity acceleration and deceleration variables, and thus, could be described as representing higher intensity change of direction actions. In the sport of American football, most change of direction activities take place over short distances within smaller spaces at moderate to high rates of change in velocity. In an analysis of football-specific drills and their influence on training load metrics in professional American football, Ward (2018) found that change of direction drills such as the pro agility shuttle and the sprint-and-turn had a more profound impact on acceleration and deceleration variables as a result of an inertial movement analysis when compared to simple linear activity such as forward running.

Principal component 2 consisted of max speed, total distance, high speed running, speed intensity, high metabolic load distance, and explosive distance with the highest coefficient (.915) being high speed running. Based on these variables, this component could be described as representing more linear based activities such as forward running or jogging over longer distances and larger areas of space allowing for more time to reach higher speeds. While many of these metrics have not been examined within the sport of American football, it has been shown that in more linear running-based sports, such as soccer where longer distances are covered over larger areas of space, metrics such as total distance, high speed running, and high metabolic load distance are primarily used to monitor athlete training load. Therefore, they have been suggested to be most appropriate for monitoring athlete training load in a sport with physiological movement demands centered on linear running-based activities (Oliveira et al., 2020).

Principal 3 consisted of dynamic stress load, total loading, and impact zones 2-6. Based on these variables, this component could be described as representing whole body mechanical loading. While running-based activities influence these accelerometer-only derived metrics, other football related activities such as change of direction, collisions, and contact also affect these metrics. Ward (2018) noted, “the impacts metric is influenced most by collision-based actions…as such, these sensors have potential to be used for quantifying the on-field demands of athletes in the sport of American football, during real training activities” (p. 57).

Kalkhoven, Watsford, Coutts, Edwards, and Impellizzeri (2020) described mechanical loading as the forces experienced by specific tissues or biological structures and can be externally or internally sourced. In the sport of American football, whole body mechanical loading would describe the forces experienced by the human body (biological structure) during practices, training, and games. Since principal component 3 consists of variables generated from the accelerometer only, the construct of whole body mechanical loading could be used to monitor athlete training load when a global positioning signal is not available such as during indoor practices.

Meanwhile, principal 4 consisted of lower intensity (zones 1 and 2) accelerations and decelerations, and thus, could be described as representing low intensity change of direction actions. These change of direction activities could take place over more moderate distances and areas of space, but do not require a maximal effort (i.e., does not need to cover distance as fast as possible). For example, during football practices athletes many times move laterally, backwards, or diagonally to practice tactical or technical elements of their specific position without giving maximal effort (and thus higher velocities). These types of drills allow for coaching and preparing for a variety of game scenarios. During practice, these types of actions can be add up to a significant amount of training load (Ward, 2018).

Finally, principal 5 consisted of average heart rate and heart rate exertion, which could be described as an internal load. Heart rate indices are commonly used to assess the relative biological stress imposed on an athlete during training or competition (Bourdon et al., 2017). To the author’s knowledge, only one study (DeMartini et al., 2011) has examined heart rate indices within American football players during practice or competition. While this study did not analyze heart rate exertion values, the authors did compare maximal and average heart rate measures between non-linemen and linemen, as well as between starters and non-starters.

DeMartini and colleagues reported a significantly higher maximal heart rate for non-linemen than linemen, but found no differences in average heart rate when comparing non-linemen to linemen. As the authors noted, “this result was somewhat unexpected given that heart rate max was greater in non-linemen during position drills and total practice time” (DeMartini et al., 2011, p. 2942). The authors went on to point out that although non-linemen elicited a greater heart rate max, covered more distance, and had shorter absolute rest, linemen likely engaged in more anaerobic work compared with non-linemen. Therefore, during football practice, a heart rate exertion measure (or a form of weighted heart rate score) could be beneficial to capturing a more accurate reflection of the internal stress of the session.

Within this study population, Tuesday and Wednesday practices occurring earlier in the week consisted of regular football training (e.g., athlete-on-athlete technical drills, full contact/collision tackling, and blocking contact). Since these 5 principal components were determined from an analysis these practices, it can be theorized that these constructs are the most appropriate to monitor training load in American collegiate football players during regular football practice and training. Furthermore, if regular football practice occurs indoors, the whole body mechanical loading construct and the internal load construct may be used to monitor athlete training load without relying on running-based data estimates from an algorithm.

However, during the in-season period, not all football training will consist of regular football activities. In this analysis, practice data from Sundays and Thursdays were examined to determine which components explained most of the variance using non running based metrics from indoor practices that were distinctly different during the in-season period. There were 3 principal components that may be described as high magnitude, whole body mechanical loading, whole body mechanical loading, and internal loading.

Principal component 1 consisted of dynamic stress load and higher magnitude impacts, while principal 2 consisted of total loading and lower magnitude impacts. Since dynamic stress load is an impact score where higher magnitude impacts are weighted more heavily (similar to heart rate exertion), it makes sense that it would be a significant variable in principal component 1, along with higher magnitude impacts such as impact zones 4 and 5 displaying coefficients of

.969 and .946, respectively. Meanwhile, total loading is a variable that sums the squares of all impacts and with all impacts weighted equally regardless of magnitude. Thus, this construct may best represent whole body mechanical loading without taking into account external intensity (i.e., the magnitude).

Study 2

The purpose of this investigation was to analyze the effect of a periodized training program on countermovement jump (CMJ) performance two 4-week training blocks (8 weeks total) in American collegiate football athletes. Subjects (n = 5) completed 2 countermovement jumps sessions every Wednesday for the total duration of 8 weeks, which produced a total of 16 jumps per subject (80 jumps analyzed). The interaction between time and measurements was significant (<.001) across most countermovement jump variables including jump height, relative mean force, peak velocity, flight time-to-contraction time ratio, reactive strength index modified, and eccentric duration. Based on partial η^2, the amount of variance in countermovement jump variables due to the effect of time ranged from 42.2% to 78.3%.

Table 4.9 Tests of Between-Subjects Effects

Tests of Between-Subjects Effects							
Source		Type III Sum of Squares	df	Mean Square	F	Sig.	η^2
Jump Height							
Intercept	Hypothesis	20183.481	1	20183.481	264.178	.000	.985
	Error	305.605	4	76.401			
Time	Hypothesis	22.766	7	3.252	7.735	.000	.659
	Error	11.773	28	.420			
Relative Mean Power							
Intercept	Hypothesis	86303.522	1	86303.522	353.007	.000	.989
	Error	977.923	4	244.481			
Time	Hypothesis	107.158	7	15.308	2.941	.019	.424
	Error	145.747	28	5.205			
Relative Mean Force							
Intercept	Hypothesis	75958.975	1	75958.975	755.843	.000	.995
	Error	401.983	4	100.496			
Time	Hypothesis	99.724	7	14.246	14.378	.000	.782
	Error	27.743	28	.991			

			Peak Velocity				
Intercept	Hypothesis	663.379	1	663.379	1277.360	.000	.997
	Error	2.077	4	.519			
Time	Hypothesis	.128	7	.018	5.738	.000	.589
	Error	.089	28	.003			
			Flight Time-to-Contraction Time Ratio				
Intercept	Hypothesis	63.975	1	63.975	222.599	.000	.982
	Error	1.150	4	.287			
Time	Hypothesis	.137	7	.020	14.472	.000	.783
	Error	.038	28	.001			
			Reactive Strength Index Modified				
Intercept	Hypothesis	32.935	1	32.935	131.332	.000	.970
	Error	1.003	4	.251			
Time	Hypothesis	.097	7	.014	8.109	.000	.670
	Error	.048	28	.002			
			Eccentric Duration				
Intercept	Hypothesis	15257424.612	1	15257424.612	109.546	.000	.965
	Error	557112.700	4	139278.175			
Time	Hypothesis	41109.288	7	5872.755	12.448	.000	.757
	Error	13209.900	28	471.782			
			Concentric Duration				
Intercept	Hypothesis	3741557.512	1	3741557.512	219.453	.000	.982
	Error	68197.800	4	17049.450			
Time	Hypothesis	8837.188	7	1262.455	3.343	.010	.455
	Error	10575.000	28	377.679			

Countermovement jump variables with the largest proportion of variance explained due to the effect of time were flight time-to-contraction time ratio, relative mean force, and eccentric duration with >70% of their variance explained by the effect of time. 78.3% of the variance in flight time-to-contraction time ratio was explained due to time, while 78.2% and 75.7% of the variance in relative mean force and eccentric duration were explained by the effect of time, respectively. The smallest proportion of the variance explained by the effect of time was in relative mean power at 42.4%.

Tukey post-hoc analyses were conducted to make comparisons between different points in time, which allowed for mean difference trends to be interpreted. Table 4.10 provides a description of CMJ performance over the duration of the 8 weeks. While significant reductions (i.e., negative mean differences) in both countermovement jump output and strategy variables were seen during the initial 4-week training block, significant improvements due to the effect of time were seen in consistently in countermovement jump strategy variables during the second 4-week training block. For example, significant improvements in flight time-to-contraction time ratio were noted in each subject during all of weeks 7 and 8.

Table 4.10 Group Means ± Standard Deviations of Countermovement Jump Performance During 8-Week Training Program

Variable	Time (week)	Mean	Standard Deviation
Jump Height (inches)	1	16.77	1.96
	2	15.83	2.36
	3	15.12	2.41
	4	15.08	2.20
	5	16.14	2.10
	6	15.82	1.92
	7	16.01	1.87
	8	16.30	1.87
Relative Mean Power (W/kg)	1	34.77	4.18
	2	32.18	4.19
	3	31.66	5.03
	4	30.99	4.10
	5	34.07	4.54
	6	33.14	3.67
	7	32.75	2.49
	8	33.20	2.55
Relative Mean Force (N/kg)	1	28.46	2.40
	2	29.96	2.11
	3	30.86	2.49
	4	31.60	2.86
	5	30.59	2.76
	6	31.00	2.72
	7	31.81	1.96
	8	32.23	2.11
Peak Velocity (m/s^2)	1	2.95	0.15
	2	2.87	0.19
	3	2.82	0.20
	4	2.82	0.18
	5	2.89	0.16
	6	2.88	0.16
	7	2.88	0.16
	8	2.89	0.15
Flight Time-to-Contraction Time Ratio	1	0.91	0.11
	2	0.85	0.11
	3	0.84	0.13

	4	0.83	0.13
	5	0.89	0.14
	6	0.90	0.14
	7	0.93	0.12
	8	0.95	0.11
Eccentric Duration (ms)	1	445.40	77.59
	2	455.20	83.64
	3	458.40	97.48
	4	462.30	100.33
	5	435.80	90.71
	6	433.20	96.73
	7	408.90	87.68
	8	394.50	75.71
Concentric Duration (ms)	1	215.20	35.02
	2	225.90	35.71
	3	223.60	38.62
	4	232.90	42.04
	5	216.60	34.85
	6	207.70	23.50
	7	210.80	36.34
	8	197.40	27.32
Reactive Strength Index Modified (JH in m/CT)	1	0.66	0.10
	2	0.61	0.11
	3	0.59	0.12
	4	0.58	0.12
	5	0.65	0.13
	6	0.66	0.12
	7	0.67	0.11
	8	0.68	0.11

A similar trend was seen in some jump output variables such as relative mean force, which displayed significant improvements for nearly all subjects in 7 and 8, however this trend was not as consistent. It did appear that changes during the second 4-week training block were generally positive, especially during weeks 7 and 8, nevertheless significant mean differences were not consistent across all or individuals, or across all jump output variables. For example, during weeks 7 and 8, there were both significant reductions and improvements in relative mean power between different individuals. This trend was also seen in jump height and peak velocity, which both displayed significant reductions and improvements throughout the second 4-week training block, including during weeks 7 and 8.

Discussion

The purpose of this examination was to analyze the effect of a periodized training program on CMJ performance over two 4-week training blocks (8 weeks total) in American collegiate football athletes. It was found that periodized training loads significantly affected CMJ performance over the course of the 8 weeks with contrasting trends during the separate training blocks. Moreover, it was found that CMJ output variables responded differently to progressively training loads over the entirety of the 8 weeks in this population, when compared to CMJ strategy variables.

While this type of study is novel within this population, other scholars have reported similar findings in other athletic populations. Gathercole et al., (2015c) found positive effects of a 8-week linearly periodized, training program on CMJ variables including force and power indices, as well as CMJ strategy variables such as eccentric duration, force at zero velocity, and eccentric rate of force development. In agreement with the findings of this study, Gathercole and colleagues reported a greater magnitude of change in jump strategy (or ‘alternative’ type) variables when compared to jump output (or ‘typical’ type) variables.

While other researchers have reported marked increases in jump output variables such as jump height, peak velocity, and force and power indices, these investigations have used recreationally trained subjects (Cormie, McBride, & McCaulley, 2009; Cormie, McGuigan, & Newton, 2010a,b; Jakobsen et al., 2012). In an elite athletic population, it has been found that 4 weeks of strength and power focused training did not improve CMJ power indices (Argus, Gill, Keogh, McGuigan, & Hopkins, 2012). McMaster, Gill, Cronin, and McGuigan (2011) suggested that after as little as a year of consistent strength and power training improvements in power measures slow dramatically. Since the population of this study were a group of American collegiate football athletes whom have engaged in at least 3 years of training in a collegiate strength and conditioning program, it could be theorized that the extent to which improvements in power indices may take place is limited (McMaster et al., 2011).

CMJ strategy variables displayed significant positive changes during the second 4-week training block, including flight time-to-contraction time ratio and eccentric duration. Since the changes in concentric duration were relatively small (45.5%) in comparison to changes in eccentric duration (75.7%), it can be deduced that improvement in flight time-to-contraction time ratio were mainly from improvements in eccentric function during the unweighting and braking phases of the jump. Hence, over the course of the training blocks, participants appeared to become more efficient in their movement strategy. It has been suggested that enhanced eccentric capacity is a product of improved stretch-shortening cycle function, which could be attributed to enhanced musculotendinous stiffness and/or mechanical efficiency (Cormie et al., 2010b; Gathercole et al., 2015c).

Study 3

The purpose of this investigation was to examine the effect of acute fatigue on CMJ performance in American collegiate football athletes. Subjects (n = 5) completed 3 countermovement jump (CMJ) testing sessions during the study period with each subject completing a total of 9 jumps (3+3+3). Changes in CMJ variables ranged from moderate to very large using group effect sizes. Subjects displayed moderate reductions in most outcome variables: relative mean power (-0.78), peak velocity (-0.69), and jump height (0.73) immediately following the training session. However, these moderate reductions were returning towards baseline 24 hours following the training session with small reductions -0.30, -0.29, and -0.27, respectively.

There was a small increase in mean force production (0.17) immediately following the training session, which also remained 24 hours post-training (0.23). Subjects displayed a large reduction in FT:CT (-1.20) and RSI modified (-1.24) immediately following training at 0 hours, which remained at 24 hours (-1.08 and -1.05, respectively). Meanwhile, eccentric and concentric duration both increased immediately following training (1.93 and 0.71, respectively) and remained at 24 hours (1.92 and 0.63).

Table 4.11 Group Mean ± Standard Deviation, Effect Size, and Interpretation for Baseline, 0 Hours, and 24 Hours Post-Training

	Baseline	0 Hours Post-exercise		24 Hours Post-exercise	
Variable	**(Mean ± SD)**	**(Mean ± SD)**	**Effect Size**	**(Mean ± SD)**	**Effect Size**
		Output Variables			
MP (W/kg)	35.8 ± 7.63*	31.1 ± 3.77	-0.78, M ↓	33.9 ± 4.5	-0.30, S ↓
MF (N/kg)	26.73 ± 1.21***	26.98 ± 1.75	0.17, S ↑	27.09 ± 1.87	0.23, S ↑
PV (m/s^2)	2.92 ± 0.22**	2.79 ± 0.15	-0.69, M ↓	2.85 ± 0.26	-0.29, S ↓
JH (inches)	16.11 ± 2.64**	14.49 ± 1.69	-0.73, M ↓	15.53 ± 1.54	-0.27, S ↓
		Strategy Variables			
FT:CT	0.94 ± 0.17*	0.79 ± 0.05$^{\wedge}$	-1.20, L ↓	0.80 ± 0.07	-1.08, M ↓
EccDur (ms)	409 ± 36*	472 ± 29$^{\wedge}$	1.93, VL ↑	481 ± 39	1.92, VL ↑
ConDur (ms)	221 ± 32*	244 ± 33$^{\wedge}$	0.71, M ↑	241 ± 32	0.63, M ↑
RSImod (JH in m/CT)	0.67 ± 0.16*	0.52 ± 0.06	-1.24, L ↓	0.54 ± 0.07	-1.05, M ↓

*Significant difference at <.001 when compared to 0 hours and 24 hours
**Significant difference at <.001 when compared to 0 hours only
***Significant difference at <.001 when compared to 24 hours only
^Significant difference at <.05 when compared to 24 hours only

Results from an ANOVA revealed statistically significant differences in CMJ variables based on time. A Tukey post-hoc analysis was used to compare different points in time. Significance was determined at the $p < .001$ and $p < .05$ levels and are marked accordingly in table 4.9. Relative mean power, eccentric duration, concentric duration, and reactive strength index modified were all significantly difference ($p < .001$) at 0 hours and 24 hours when compared to baseline. Meanwhile, jump height and peak velocity were statistically different (<.001) when comparing baseline to 0 hours only, as measurement values were trending back towards baseline at 24 hours.

Flight time-to-contraction time ratio was significantly different (<.001) at 0 hours and 24 hours when compared to baseline. Similarly, the concentric duration and reactive strength index modified measures at 0 hours were significantly ($p < .05$) different when compared to 24 hours. Finally, relative mean force was significantly difference ($p < .001$) at 24 hours when compared to baseline only.

Discussion

The purpose of this examination was to analyze the effect of acute fatigue on CMJ performance in American collegiate football athletes, while determining the efficacy of using the CMJ test to monitor neuromuscular fatigue in American collegiate football athletes. It was found that fatigue as result of a football-specific training session effected countermovement jump variables considerably with effect sizes ranging from moderate to very large. While both CMJ output and strategy variables were effected by fatigue from the football-specific session, it appeared that strategy variables were altered to a greater degree with larger effect sizes. Moreover, CMJ strategy variables remained significantly altered after 24 hours, while CMJ output variables demonstrated only small reductions.

Gathercole et al. (2015c) examined CMJ performance in response to acute neuromuscular fatigue in elite snowboard athletes, while considering ‘typical’ (i.e., output) versus ‘alternative’ (strategy) countermovement jump variables. Similarly to this investigation, Gathercole and colleagues conducted their study using the magnitude of change via effect sizes. The authors reported that both typical and alternative variables were reduced with effect sizes ranging from trivial to large. However, in alignment with the reports from this investigation, the authors found that the largest effect sizes were associated with alternative countermovement jump variables (Gathercole et al., 2105c).

In this investigation, it was found that during the immediate post-exercise testing period (0 hours) the CMJ variable that appeared to have been altered the most with an effect size of 1.93 (very large) was eccentric duration. This finding is in agreement with those of Gathercole et al. (2015c) in which the authors noted a 1.91 effect size of eccentric duration during the testing period immediately following the training session. Similarly, this investigation found that eccentric duration remained altered to a very large degree (-1.92) at 24 hours, which was consistent with other groups reporting reductions in jump strategy variables persisting 24 hours after training (Gathercole et al., 2015b; Kennedy & Drake, 2017).

Similar to the findings from Kennedy and Drake (2017) and Gathercole et al. (2015b), the findings from this study demonstrate that while CMJ output variables were trending towards baseline levels at 24 hours, jump strategy variables remained significantly reduced. In particular, it appears that the eccentric portion of the jump may display the most altered characteristics, and thus, be taken into consideration when assessing neuromuscular fatigue. The magnitude of change of CMJ strategy variables in this study were greater than those from previous reports, which most likely reflects differences in populations and the fatigue-induced protocol used (Claudino et al., 2016; Halson, 2014; Kennedy & Drake, 2017).

In addition, Gathercole and colleagues reported a small magnitude increase in concentric duration and a reduction in eccentric and concentric power indices. These findings are collaborated by this analysis in which a moderate increase in concentric duration was reported, along with moderate or large reductions in other CMJ strategy and output indices during the 0 hour post-exercise period including jump height, peak velocity, relative mean power, flight time-to-contraction time ratio, and reactive strength index modified. Similar findings have been reported in other investigations by this group (Gathercole et al., 2015b), as well as others (Cormie et al., 2010a, b; Kennedy & Drake, 2017).

The increases in eccentric and concentric duration reported in this study, and by Gathercole et al. (2015b, 2015c) and Kennedy and Drake (2017), demonstrate a change in CMJ strategy as a result of fatigue. In this examination, flight time-to-contraction time ratio and reactive strength index modified were also altered to moderate degree during the post-exercise period, while Gathercole and company reported changes in force at zero velocity and eccentric impulse (Gathercole et al., 2015b,c).

Moreover, these alterations in CMJ mechanics appear to be associated with larger post-exercise changes than CMJ output variables such as jump height, relative mean force, and relative mean power. Indeed, CMJ strategy (or alternative type) variables such as flight time-to-contraction time ratio, eccentric and concentric duration, and reactive strength index modified may provide greater insight into, and possibly sensitivity to, neuromuscular fatigue than jump output variables such as jump height, peak velocity, relative mean force, and relative mean power (Gathercole et al., 2015b, c; Kennedy & Drake, 2017).

It has been reported that skilled performers have greater movement variability, which allows them to self-organize and adapt in dynamic environments (Davids, Glazier, Araujo, & Bartlett, 2003). The considerable alterations in jump strategy variables reported in this study, as well as those reported by others (Gathercole et al., 2015c; Kennedy & Drake, 2017), suggest that athletes self-organize and adopt new movement strategies to achieve maximal performance in a given task (Davids et al., 2003; McBride & Synder, 2012). In the context of fatigue and jump strategy, it appears that fatigued athletes self-organize to select a movement strategy that provides them with maximal physical output in the jumping task (Rodacki, Fowler, & Bennett, 2002). Hence, monitoring mechanical variables that demonstrate *how* the jump occurred may be efficacious (Gathercole et al., 2015c).

Although most CMJ output variables were moderately reduced, this analysis revealed a small increase in relative mean force production. This is in contrast to the findings from Gathercole et al. (2015c). Gathercole and colleagues reported a reduction in force production indices, however they reported small increases in peak velocity and jump height; contradictory to the findings of this study. While these findings are in contrast, there seems to be less consistency regarding the effect of fatigue on CMJ output variables. While some studies have reported increases in power variables (Boullosa et al., 2011; Cormack et al., 2008), others have reported no change (Hoffman et al., 2002; Hoffman et al., 2003; Johnston et al., 2013) and decreases (Gathercole et al., 2015b; McLellan, Lovell, & Gass, 2011). Similar inconsistencies have been reported when examining force production variables (Boullosa et al., 2011; Cormack et al., 2008; Gathercole et al., 2015b; McLellan et al., 2011).

These inconsistencies could be attributed to differences in populations, fatiguing protocols, testing protocols, athlete training status, or genetic makeup (Claudino et al., 2016; Halson, 2014; McGuigan, 2017). Hoffman et al. (2002) examined squat jump and CMJ performance before, during, and after a division III American collegiate football game. The authors reported study participants being able to maintain performance in the CMJ to a greater degree than the squat jump. The authors attributed this to the CMJ utilizing the stretch shortening cycle, which may mean that the intensity of the game had a less fatiguing effect on neuromuscular factors mediating the stretch shortening cycle.

It should be noted that the examination by Hoffman et al. (2002) did not capture strategy-related variables during the countermovement jump. Thus, there was no way to quantify how jump strategy may have been altered due to the occurrence of fatigue. Gathercole et al. (2015c) reported only a small reduction in force production with a large magnitude of change in eccentric duration. This may indicate that as athletes become fatigued, they spend more time contracting during the unweighting, braking, and propulsive phases of the countermovement jump. It could be theorized that an increase in contracting time could allow athletes for time to apply force. The magnitude of change in eccentric and concentric duration in the present study was to a greater degree than those reported by Gathercole et al. (2015c). Hence, it could be theorized that increased total time spent contracting attributed to the small increase in relative mean force.

An interesting finding from this study was that 24 hours after cessation of exercise, participants still had moderate to large reductions in most CMJ output and strategy variables. The largest reductions were in jump strategy variables, which supports the possibility of jump strategy variables providing more insight into the recovery—fatigue time course. Future research could investigate the time course of recovery of CMJ performance from other football-related training. In the present study, participants were brought in to train 24 hours later making the assessment of acute fatigue at 48 hours confounded. Thus, future research could provide insight into the time course of recovery in American football training.

Chapter 5

General Discussion

This line of research illustrated the efficacy of using a systematic framework to monitor athletes within the sport of American football, while demonstrating the use of athlete monitoring tools used in a variety of other sports within the sport of American football. These aims were accomplished through achieving the following objectives: 1) quantifying the physical demands of American collegiate football practice and examining the influence of position groups on these physical demands, 2) examining relevant athlete monitoring metrics commonly used to monitor athlete training load in sport to determine which of these metrics may be most suitable for use in American football, 3) demonstrating the suitability of the using the countermovement jump (CMJ) in assessing adaptations to training and fatigue within the sport.

While American football is one of the most popular and wealthiest sports in the world, there are limited scientific resources available to practitioners to guide in the development and implementation of an evidence-based sport preparation program (Ward, 2018; Wellman et al, 2016). The primary aim of this line of research was to develop a framework to guide American football practitioners in establishing an athlete monitoring program. The studies carried out within this line of research were intended to provide guidance pertaining to the most appropriate constructs and variables for use within the sport, while situating their use within the proposed framework. Thus, American football practitioners should be able to use this athlete monitoring framework as guide in not only selecting athlete monitoring tools, but also in identifying how to monitor a particular construct and which variables to select for monitoring based on their own organizational context.

A comprehensive athlete monitoring program quantifies the stress during training, practice, and competition, assesses athlete fitness and fatigue throughout the year, assesses non-training parameters that influence athlete training, adaptations, and performance, and evaluates key individual factors that may influence any of the aforementioned areas. In combination, the athlete monitoring data collected from these areas should assist in minimizing the risk of injury and maximizing the performance potential of the athlete, while enhancing athlete health and wellness which undergirds any performance-related outcomes.

In American football, athlete monitoring data has been used to explore injury reduction (Sampson, Murray, Williams, Sullivan, & Fullagar, 2019; Wilkerson, Gupta, Allen, Keith, & Colston, 2016), examine return-to-play characteristics (Forsdyke, Gledhill, & Ardern, 2016), investigate athlete wellness and well-being (Sampson et al., 2019), describe physical characteristics of athletes within the sport (Anzell et al., 2013; Fry & Kraemer, 1991; Garstecki et al., 2004), examine cardiovascular health (Feairheller et al., 2016; Kim et al., 2018), quantify the stress of training and competition (DeMartini et al., 2011; Hoffman et al., 2005; Ward, 2018; Wellman et al., 2016, 2017), and analyze the efficacy of strength and conditioning programming for sport (Hoffman et al., 2004; Iaia, Rampinini, & Bangsbo, 2009; Morris, 2015). Indeed, there is a growing evidence base connecting athlete monitoring data with athlete health and safety, as well as performance-related outcomes within the sport.

Meanwhile, practitioners are faced with unique challenges specific to their organizational context, including available resources and personnel, openness to interdisciplinary coordination (e.g., strength and conditioning, sports medicine, sports nutrition), and accessibility of skillsets to establish an athlete monitoring program. Thus, practitioners are challenged to develop an athlete monitoring program that fits within their organizational context, despite the opportunity to connect their programmatic efforts to the growing evidence-base being established within the sport. With this in mind, the conceptualization of a simplistic framework to guide practitioners across differing organizational contexts was developed.

While the framework is intended to guide American football practitioners across different organizational contexts, this line of research is intended to assist practitioners in understanding which variables may be most appropriate for monitoring areas such as the quantification of training stress and the assessment of fitness and fatigue. As noted by Thornton, Delaney, Duthie, and Dascombe (2019), there is an extensive range of monitoring tools and technologies, which make selecting and utilizing the most appropriate variables challenging. The variables utilized within this line of research were selected based on their appropriateness for the sport and their use in the American football body of literature.

Based on the findings from study 1, practitioners should be able to develop a daily training load report utilizing the five constructs reported from the principal component analysis. Moreover, since these variables were selected for analysis based on the body of literature in American football, practitioners should be able to connect their training load data with variables currently being examined within the sport. For example, the training load constructs determined in study 1 could be used to track daily training load, establish an acute:chronic (AC) workload ratio, and monitor changes in training load based on the suggested guidelines from Sampson, Murray, Williams, Sullivan, and Fullagar (2019; avoiding daily changes >1 SD) and Gabbett (2016; 0.8-1.3 AC ratio sweet spot). In this example, a practitioner could use this line of research to streamline their data collection and analysis efforts allowing for evidence-based practice within the sport.

In addition, monitoring training load variables as presented in study 1 should allow practitioners to develop measures of central tendency, such as a daily mean (or a moving average), and measures of variability such as a daily standard deviation. These measures could then be used to create positional thresholds through which ‘spikes’ or reductions in daily training load could be captured and communicated to the coaching staff. This allows for fitness to be maintained in the case of training load reductions (McGuigan, 2017), or, in the case of training load spikes, allows for the prevention of non-functional overreaching or overtraining (Gabbett et al., 2017; Windt et al., 2017).

Studies 2 and 3 provided insight into assessing fitness and fatigue using the CMJ in American collegiate football athletes. Study 2 found that monitoring jump strategy variables, such as the flight time-to-contraction time ratio and eccentric duration, may provide more insight into training adaptations than monitoring jump output variables only within this highly trained population. Meanwhile, the results from study 3 suggest that these same jump strategy variables may be more sensitive to fatigue than jump output variables. Based on these studies, practitioners could establish non-fatigued baseline values over the course of a week, which would take into account normal daily variation, and use the CMJ to monitor athlete readiness or evaluate the effectiveness of a training program (Joyce & Lewindon, 2014; McGuigan, 2017). Thus, practitioners may find it efficacious to monitor such CMJ strategy variables as flight time-to-contraction time ratio, eccentric and concentric duration, and reactive strength index modified. Finally, findings from these investigations provide some reference values for American football practitioners to utilize.

When interpreting the findings from study 3 with those of Gathercole et al. (2015b,c) and Kennedy and Drake (2017), it can be suggested that jump strategy variables such as eccentric duration, concentric duration, force at zero velocity, flight time-to-contraction ratio, reactive strength index modified, and eccentric rate of force development may be the most sensitive to fatigue, while providing the most insight into the severity of fatigue. Similarly, findings from study 2 suggest that monitoring these jump strategy variables may provide more insight into training adaptations (e.g., possibly through enhanced SSC function) in highly trained American football athletes.

Therefore, the proposed athlete monitoring framework and this line of research provide practitioners with guidance pertaining to which variables to collect, and what these variables represent, for the purpose of monitoring training adaptations and fatigue. Once collecting these data, practitioners can monitor daily and weekly changes in these variables to reflect best practices in applied sports science such as intra-individual changes >2 SD, or changes >1.5 in Z-scores when comparing inter-individual changes (McGuigan, 2017; Schuster, Bove, & Little, 2020).

Fundamental to designing an athlete monitoring program is determining the physiological and biomechanical demands of the sport. This allows practitioners to design appropriate training regimens, develop and implement appropriate practice drills, and assess athlete fitness for competition (McGuigan, 2017). The sport of American football requires a multitude of dynamic movements, including linear forward sprinting, backpedaling, angled cutting, and jumping, while performing these movements in an acyclic pattern—integral functions performed in one action (Pincivero & Bompa, 1997). Furthermore, the volume and intensity of these movements are dependent upon the position being played (Wellman et al., 2016, 2017).

Given the varied movements and characteristics of the sport, integrated microtechnology serves as an effective tool to monitor the external training load of American football athletes (Ward, 2018; Wellman et al., 2016, 2017). Constructs reported in chapter 4 illustrate how these varied movements and characteristics of sport could be used to quantify movement profiles and determine the physical demands of training and competition. These data can then be used to ‘reverse engineer’ the training process, and design training and practice regimens that prepare athletes for the demands of the sport. For example, variables found in the first two training load constructs from the PCA, such as accelerations/decelerations in zones 5/6 and high speed running, can be used as training variables in speed and conditioning programs to systematically progress working backwards towards the required demands in practices and games. This ensures proper progressions (e.g., ≤10% weekly increase in volume) and preparation specific to the demands of the sport (Gabbett et al., 2017).

Meanwhile, American football athletes must have energy systems equipped to support short, intermittent, high intensity activities requiring high anaerobic power outputs and high static force production spread out over a long duration (Kraemer, 1997; Pincivero & Bompa, 1997). Previous investigations have explored energy system requirements by assessing work-to-rest ratios during games (Iosia & Bishop, 2008; Rhea et al., 2006). These investigations have provided insight into how to appropriately design sport-specific, periodized programs based on the metabolic demands of the sport. Nevertheless, monitoring devices that capture the internal physiological demand of training and practice is invaluable in assessing training load and fitness.

Heart rate indices in the sport of American football have been reported sparingly. To the author’s knowledge, the only peer-reviewed investigation monitoring heart rate during American football practice or during a game was DeMartini et al. (2011). Due to the short, intermittent, high intensity nature of football, average heart rate values may not be reflective of capturing positional differences in the internal demands of the sport (DeMartini et al., 2011). However, due to the prolonged nature of the intermittent, high intensity sport, weighted heart rate indices that reflect time spent in higher heart rate zones may be of use to practitioners for monitoring the internal response to given external training loads (DeMartini et al., 2011; Joyce & Lewindon, 2014).

Although the sport of American football involves short (~5 seconds), intermittent activities consisting of high anaerobic power outputs with rest periods ranging from 7 to 12 times that of the work period and are performed over a long duration, much of the off-season conditioning of American football athletes consists of high running volumes involving shorter rest periods, longer bouts of activities, and are performed over a much shorter period of time (Iosia & Bishop, 2008). For example, appendix I displays data comparing the internal measures of sport practice to those of an off-season running based conditioning circuit. While the effectiveness of these methods could be debated, practitioners must have effective ways to monitor the training demand of sessions, while assessing improvements in fitness characteristics of the athletes over time. Thus, heart rate indices may provide usefulness as an appropriate tool to meet these athlete monitoring needs.

Based on the reports from Iosia and Bishop (2008) and Rhea et al. (2006), the author would describe American football as primarily an anaerobic alactic—aerobic sport (Gastin, 2001; Sawka, Tahamont, Fitzgerald, Miles, & Knowlton, 1980). This metabolic classification is further supported by the findings from the PCA and descriptive analyses in study #1. The loading constructs indicate repetitive, high velocity linear and non-linear movements as the top two 'principal' components, while descriptive analyses show that average heart rates remain in the 55-65% range of the age predicted max heart rate for this population. Hence, the primary energy systems utilized would be the adenosine triphosphate (ATP) phosphocreatine (PCr) and oxidative energy systems. The ATP-PCr system provides immediate energy via a chemical reaction of PCr to creatine and is the primary energy source for activities lasting <15 seconds.

Meanwhile, the oxidative system provides is the primary energy system for prolonged activities lasting >90 seconds supplying energy from primarily the oxidation of carbohydrates and fats (Tiidus, Tupling, & Houston, 2012).

It seems most appropriate to describe American football as a primarily an anaerobic alactic—aerobic sport due to the intermittent, high anaerobic power outputs required, work-to-rest ratios ranging from 1:7 to 1:12 occurring over a prolonged period of time (3-4 hours), and having extended periodic breaks (2-4 minutes between quarters and 20 minute halftime). Indeed, Fox and Mathews estimated that American football was approximately 90% ATP-PCr 10% glycolytic. While the anaerobic lactic energy system certainly contributes energy throughout a game, it could be theorized that a robust aerobic system would be of greater importance to minimize the reduction of anaerobic power output—which is related to the phosphagen splitting rate—over the course of the game through the resynthesis of phosphocreatine, as well as through the disposal of metabolic byproducts such as hydrogen that alter muscle pH (Takahashi et al., 1995; Tiidus et al., 2012).

It has been suggested that the repletion of PCr is biphasic in nature with a fast component and a slow component (Tiidus et al., 2012). With the majority of the research taking place using cycle ergometry protocols, it has been reported that half of PCr stores are resynthesized in approximately 21 seconds, while complete resynthesis took approximately 170 seconds (Harris et al., 1976). A review by McMahon and Jenkins (2002) suggested PCr repletion rates of 65%, 85%, and 95% at 90 seconds, 4.5 minutes, and 13.6 minutes, respectively. While it has been found that the fast component of ATP-PCr resynthesis is independent of muscle pH, it appears the slow component is rate dependent on the return of the muscle cell to homeostatic intracellular pH (McMahon & Jenkins, 2002; Tiidus et al., 2012). Thus, underscoring the importance of oxidative phosphorylation in the ATP-PCr resynthesis process, especially when the maintenance of anaerobic power output is paramount.

According to Iosia and Bishop (2008) and Rhea et al. (2006), an average play in collegiate football is 5 seconds and has an average rest duration of 47 seconds with an average of 6 plays occurring per series. Moreover, Rhea et al. (2006) reported an average of 13.46 series per game and an average of 1.05 minutes of stoppage per series in collegiate football. When examining the reported work-to-rest ratios in combination with the reported physical demands of the sport such as the results from the PCA in chapter 4 indicating linear and non-linear high velocities movements, it can be estimated that a collegiate football athlete must be prepared to generate ~6 high power outputs lasting ~5 seconds per series with repletion of ATP-PCr ~55-65% after the first play.

After the first play, it would appear that the contribution of energy systems would be primarily dependent upon the athlete's anaerobic alactic capacity, which is related to the magnitude of change in phosphagen concentrations within the skeletal muscle (Sawka et al., 1980). Although it has been suggested that this may provide a rationale for training focused on enhancing glycolytic capacity in support of a possible increased reliance on glycolytic metabolism and increased lactate accumulation (Hoffman et al., 2005), shifts toward glycolytic energy sources would not be ideal due to a slower energy production rate, which would reduce anaerobic power output (Tiidus et al., 2012). Thus, enhancing an American football athlete's anaerobic alactic capacity, and subsequently, their ability to perform multiple linear and non-linear movements involving high velocities and high force production may provide an ability to minimize the reduction in anaerobic power output over the course of a given practice or competition. Moreover, focusing on anaerobic alactic capacity and power compliments abilities, such as sprint speed and the vertical jump, that have been predictive of success in collegiate American football (Davis et al., 2004), while potentially increasing maximal anaerobic alactic power output, and thus, improve power production qualities found to differentiate starters from non-starters and between teams within a division regarding performance (Hoffman, 2008).

Moreover, high volume conditioning completed during the off-season as part of a ‘traditional’ football conditioning circuit has been shown to reduce the training effect of strength, speed, and power qualities in American collegiate football players (Moore & Fry, 2007). The protocol utilized by the American football practitioners in the investigation by Moore and his colleague involved several stations of drills aimed at improving speed, agility, and vertical jump height. However, most likely to the large volume of training and the work-to-rest ratios, the conditioning program actually left these performance variables unchanged or worsened. As noted by the authors, “it is likely that this protocol may have improved the ability of the subjects to tolerate a high lactic acid load…however, this quality means little when coupled with significant decrements in the critical sport-specific performance variables such as agility and sprint time” (Moore & Fry, 2007, p. 799).

Based on the training principle of specificity—training adaptations are highly specific to the type of activity and to the volume and intensity of the activity performed—it could be suggested that American football athletes perform interval training focusing on anaerobic power output and replicating the work-to-rest ratios of their sport (Joyce & Lewindon, 2014). This would be paramount during the preseason and in-season periods when the focus is specific preparation for the sport. Training prescription may address these physiological requirements through performing anaerobic alactic power, or ‘intensive’, interval training (Jamieson, 2009). Meanwhile, it would appear that a robust aerobic system expediates recovery via the removal of metabolites and the subsequent reduction in muscle pH (McMahon & Jenkins, 2002; Tiidus et al., 2012). Training prescription may address these physiological requirements through performing appropriately programmed aerobic training.

Intensive interval training would focus on enhancing (and maintaining) anaerobic power output (5-10 seconds at maximal effort for 5-10 repetitions), while selecting appropriate exercises based on the time of the year. For example, explosive dynamic movements such as jump squats, sprinting, bounding, sled pushes further away from the season, while route trees, blocking sleds, and technical drills could be used closer to the season and in-season. Aerobic training could be completed at heart rates between 120 and 140 bpm for 20-60 minutes with progressions focusing on completing activities at higher speeds or power outputs, while maintaining an average heart rate within the aforementioned range.

Aerobic training would be most efficacious when programmed during the off-season. Low-impact and high-impact modalities could be utilized based on the individual characteristics such as the athlete body type, training and injury history, and position played. Low-impact modalities include swimming, cycling, jumping rope, sled drags, sled pushes, and/or loaded carries. Meanwhile, high-impact modalities include form running intervals with active rest (e.g., walking, mobility work) between intervals. During aerobic training sessions, monitoring heart rate indices would be paramount to ensure the actual purpose (i.e., development of oxidative abilities with minimal lactate accumulation) is fulfilled.

In terms of energy system development, the athlete monitoring framework can be used to select appropriate tools to assess the training load of conditioning session, assess the resultant fatigue of the session, and monitor adaptations and fitness as a result of the conditioning program. Heart rate indices can be used to both quantify the training stress and to assess fitness, while the assessment of neuromuscular status via jump testing can be used to assess fatigue. If using heart rate to quantify training stress and monitor fitness, the concept of a training impulse (TRIMP) may be useful to practitioners.

The concept of the TRIMP was introduced to provide a single arbitrary unit suitable to monitor training load and fitness (Joyce & Lewindon, 2014). In its most simple format, a TRIMP is calculated as the product of average heart rate and the duration of the training session. However, a more effective method involves a weighting factor in which the greater stress of high intensity training is emphasized (similar to heart rate exertion). Foster and colleagues (1995) proposed a relatively simple weighting approach in which the TRIMP is calculated by multiplying the accumulated duration in each heart rate zone by a multiplier allocated to each zone (50-60% = 1; 60-70% = 2; 70-80% = 3; 80-90% = 4; and 90-100% = 5).

While this line of this research has focused on the utilization of athlete monitoring data to ultimately enhance performance, it should be noted that a byproduct of a systematic athlete monitoring program is the enhancement of overall student-athlete health and well-being (McGuigan, 2017). For example, American football athletes have been shown to be at an increased risk for cardiovascular disease due to cardiovascular risk factors such as high blood pressure, excessive body fat, and a sedentary lifestyle once their athletic career has concluded (Feairheller et al., 2016; Kim et al., 2018). Thus, monitoring data can be used for physical and educational interventions to reduce these risk factors.

Findings from this line of research can be used to inform future research. Future research could examine relationships between the training constructs identified through the PCA and training adaptations and/or fatigue. Moreover, future research could investigate the potential link between the training load constructs identified in the PCA and measures of athletic performance and/or availability. Furthermore, future investigations could explore the relationship between subjective measures of internal load, such as sessional ratings of perceived exertion, and CMJ measures in this population.

In conclusion, this line of research proposed an athlete monitoring framework and demonstrated its use within the sport of American collegiate football. In addition, this line of research extended the body of literature on American collegiate football with some novel findings relevant to practitioners. There were significant differences in the physical demands of American collegiate football practice between position groups. For Tuesday and Wednesday practices, significant ($p <.001$) group main effects were found for all physiological movement profile variables, except average heart rate.

When examining differences in the physical demands of Tuesday and Wednesday practice between position groups in the post-hoc analysis, positional differences of note include: 1) wide receivers had significantly more high speed running yards, high metabolic load distance yards, speed intensity values, and high intensity accelerations than defensive backs, 2) wide receivers and defensive backs had a similar number of high intensity decelerations, 3) defensive backs had significantly more high speed running yards than all other defensive position groups, 4) linebackers had significantly more high intensity accelerations/decelerations, impacts, and internal load values than all other defensive position groups, and 5) offensive linemen had a significantly higher heart rate exertion values than all other offensive position groups.

In addition, the PCA conducted in study #1 provided a set of 5 factors explaining approximately 81% of the variance in practice data from Tuesday and Wednesday practice. These factors representing the training constructs of high intensity COD based loading, linear running based loading, whole body mechanical loading, low intensity COD based loading, and internal loading can be used to monitor the training load in American collegiate football athletes.

In study #2, the amount of variance explained in CMJ variables due to the effect of time ranged from 42.2 to 78.3%. CMJ variables with the largest proportion of variance explained due to the effect of time were flight time-to-contraction time ratio, relative mean force, and eccentric duration (all >70%). Based on the Tukey post-hoc analysis, there were significant negative mean differences observed in both CMJ output and strategy variables during the first 4-week training block. However, significant improvements due to the effect of time in CMJ strategy variables were observed during the second 4-week training block. This was consistent in 4 out of the 5 subject IDs during weeks 7 and 8.

In study #3, changes in CMJ performance ranged from moderate to very large magnitudes of change. At 0 hours, subjects displayed moderate reductions in jump height, peak velocity, and mean power, while displaying a very large increase in eccentric duration, a moderate increase in concentric duration, and a large reduction in flight time-to-contraction time ratio. At 24 hours, CMJ output variables appeared to be recovering toward baseline with small reductions, however eccentric duration was still changed to a very large degree while concentric duration and flight time-to-contraction time ratio displayed moderate changes. Finally, all CMJ strategy variables displayed significant ($p <.001$) changes when comparing 0 hours and 24 hours to baseline, while mean power was the only CMJ output variable with that same statistical pattern.

Collectively, these findings suggest the efficacy of using integrated microtechnology, heart rate sensors, and the CMJ using a force plate testing system in the sport of American collegiate football. Moreover, these tools were used within a proposed systematic framework to monitor athletes. It was the author’s aim to contribute to the body of scholarly literature on American collegiate football, while providing a resource to help guide practitioners in their preparation of American collegiate football athletes. It is the author’s hope that this line of research has contributed to this aim.

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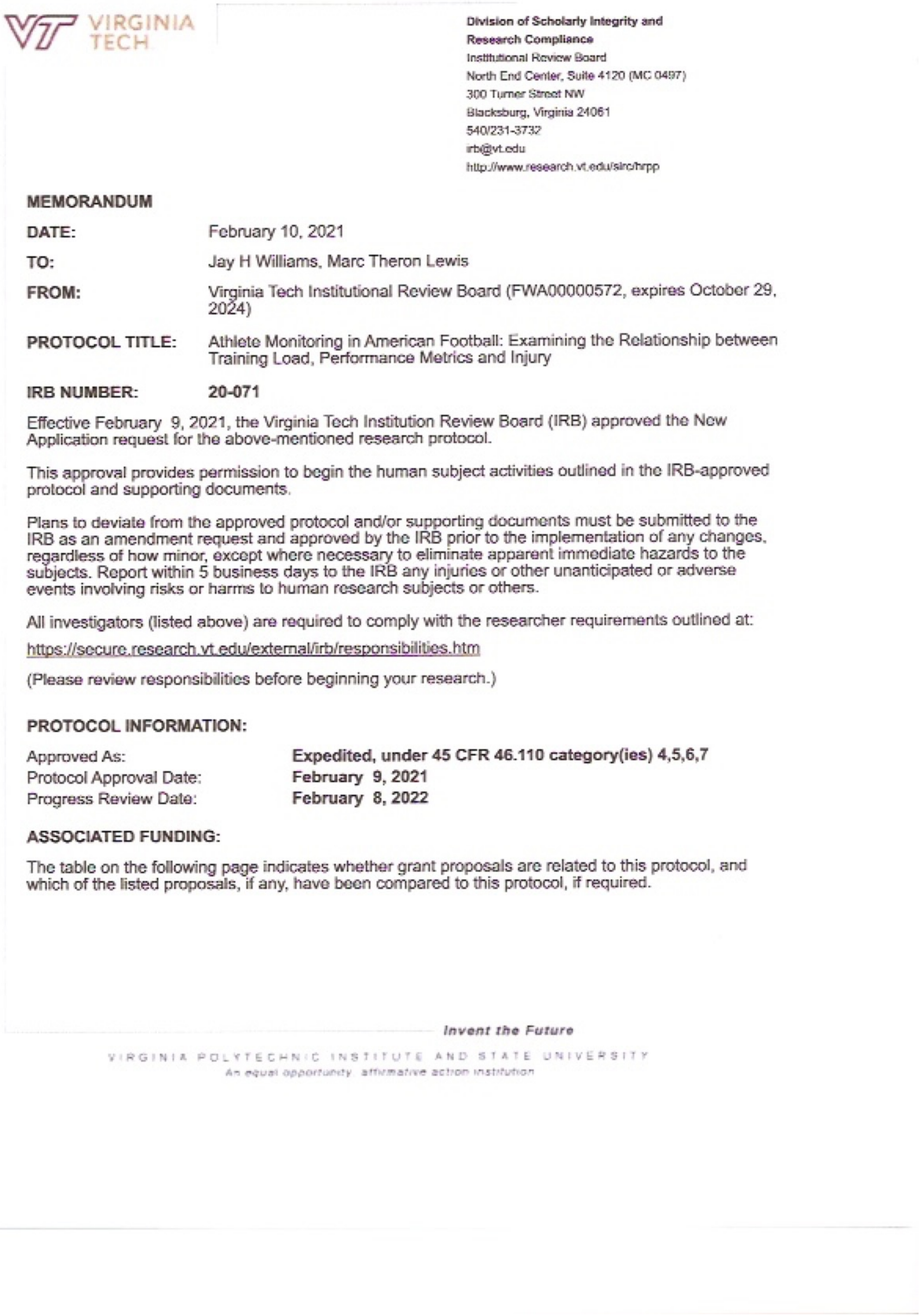
Appendices

Appendix A – Institutional Review Board Letter of Approval



VIRGINIA TECH

Division of Scholarly Integrity and Research Compliance
Institutional Review Board
North End Center, Suite 4120 (MC 0497)
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-3732
irb@vt.edu
http://www.research.vt.edu/sirc/hrpp

MEMORANDUM

DATE: February 10, 2021

TO: Jay H Williams, Marc Theron Lewis

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires October 29, 2024)

PROTOCOL TITLE: Athlete Monitoring in American Football: Examining the Relationship between Training Load, Performance Metrics and Injury

IRB NUMBER: **20-071**

Effective February 9, 2021, the Virginia Tech Institution Review Board (IRB) approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

https://secure.research.vt.edu/external/irb/responsibilities.htm

(Please review responsibilities before beginning your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 4,5,6,7**
Protocol Approval Date:	**February 9, 2021**
Progress Review Date:	**February 8, 2022**

ASSOCIATED FUNDING:

The table on the following page indicates whether grant proposals are related to this protocol, and which of the listed proposals, if any, have been compared to this protocol, if required.

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An equal opportunity, affirmative action institution

Appendix B – Informed Consent

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Consent to Take Part in a Research Study

Title of research study: Athlete Monitoring in American Football: Examining the Relationship between Training Load and Athletic Performance Metrics

Principal Investigator: Jay H. Williams, Ph.D. (Principal Investigator)
Email: jhwms@vt.edu
Phone: (540) 231- 8298

Other study contact(s): Marc T. Lewis, M.S. (Co-Investigator)
Email: marc7@vt.edu
Phone: (540) 231-2984

Key Information: The following is a short summary of this study to help you decide whether or not to be a part of this study. More detailed information is listed later on in this form.

This research is being conducted by faculty and graduate students of the Department of Human Nutrition, Foods and Exercise at Virginia Tech. The purpose of this study is to determine the relationship between physical demands of participating in varsity collegiate athletics and the risk of injury. Our goal is to establish guidelines for developing training programs that will improve competitive performance while minimizing the risk of injury. This study will provide the groundwork for those goals. You are being asked to participate because you are a member of a Virginia Tech intercollegiate varsity sports team. You have also been cleared for participation in intercollegiate athletics by medical personnel. We plan to enroll student-athletes over the course of three years. It is also important for you to know that the results from this study may be used for research publications. However, every effort to maintain confidentiality will be taken.

Why am I being invited to take part in a research study?

You are being asked to be in a research study because you are a student-athlete participating in football at Virginia Tech. It is entirely your choice. In order to decide whether you want to be a part of this study, it is important that you read and understand this form. It is also important that you ask any questions that you may have and that you understand all the information in this form. This process is called "informed consent."

What should I know about being in a research study?

- Someone will explain this research study to you
- Whether or not you take part is up to you
- You can choose not to take part
- You can agree to take part and later change your mind
- Your decision will not be held against you
- You can ask all the questions you want before you decide

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Consent to Take Part in a Research Study

Why is this research being done?

Our goal is to establish guidelines for developing training programs that will improve competitive performance while minimizing the risk of injury. This study will provide the groundwork for those goals.

How long will the research last and what will I need to do?

We are wanting to use data that is being currently being collected as part of our athlete monitoring program, which is led by Marc Lewis. If you decide to participate in this study, you will not have to engage in any other activity outside of what is normally expected of you during training and competition. We are simply asking for permission to use your data.

More detailed information about the study procedures can be found under, **"What happens if I say yes, I want to be in this research?"**

Is there any way being in this study could be bad for me?

There are no known risks associated with this study.

More detailed information about the risks of this study can be found under **"Is there any way being in this study could be bad for me? (Detailed Risks)".**

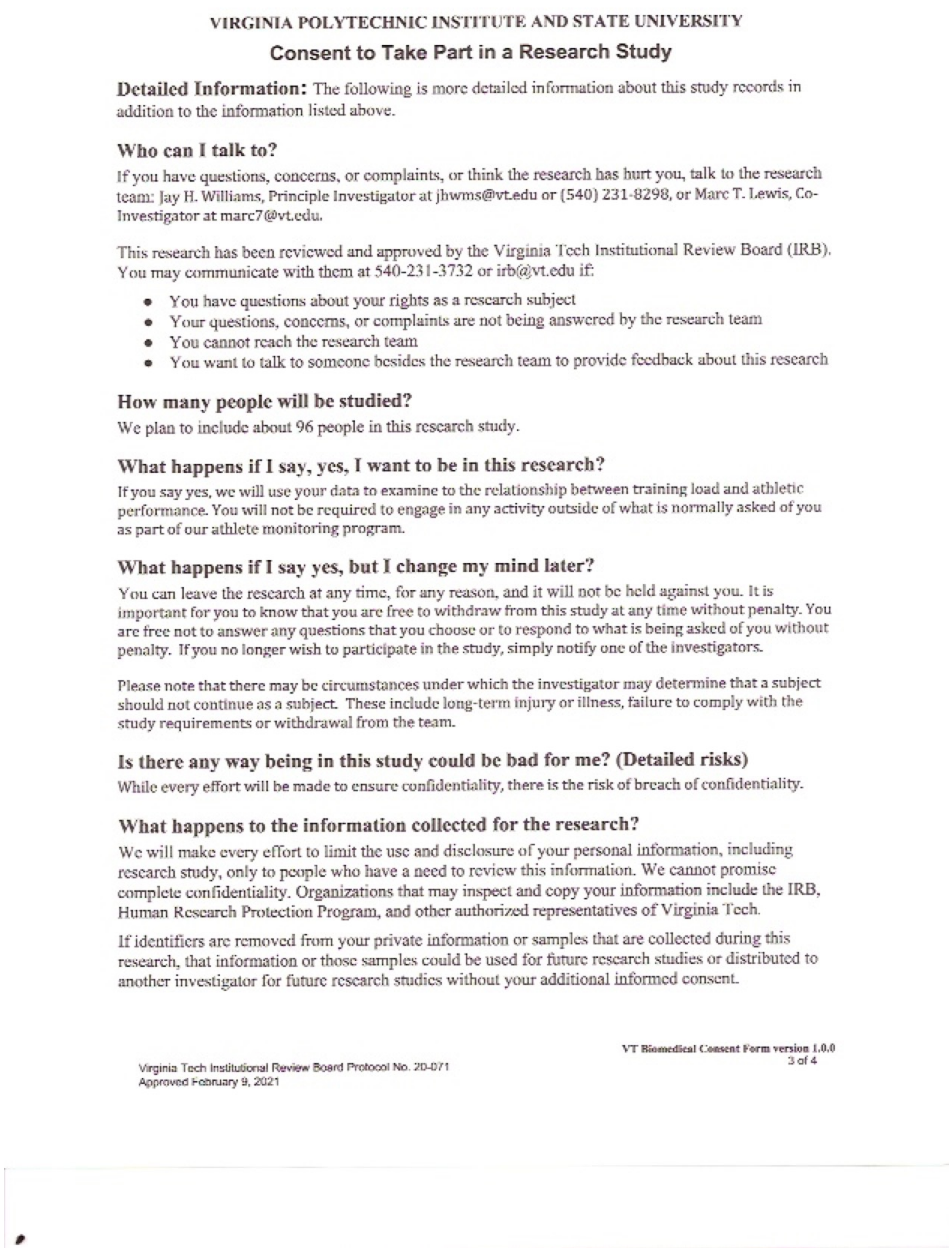
Will being in this study help me in any way?

There are no benefits to you from your taking part in this research. We cannot promise any benefits to others from your taking part in this research. However, possible benefits to others include understanding the physical demands of American football and the relationship between athlete training and performance.

What happens if I do not want to be in this research?

Participation in research is completely up to you. You can decide to participate or not to participate.

If you are a student, the decision whether to participate or not participate will have no effect on your grades or relationship with Virginia Tech.



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Consent to Take Part in a Research Study

Detailed Information: The following is more detailed information about this study records in addition to the information listed above.

Who can I talk to?

If you have questions, concerns, or complaints, or think the research has hurt you, talk to the research team: Jay H. Williams, Principle Investigator at jhwms@vt.edu or (540) 231-8298, or Marc T. Lewis, Co-Investigator at marc7@vt.edu.

This research has been reviewed and approved by the Virginia Tech Institutional Review Board (IRB). You may communicate with them at 540-231-3732 or irb@vt.edu if:

- You have questions about your rights as a research subject
- Your questions, concerns, or complaints are not being answered by the research team
- You cannot reach the research team
- You want to talk to someone besides the research team to provide feedback about this research

How many people will be studied?

We plan to include about 96 people in this research study.

What happens if I say, yes, I want to be in this research?

If you say yes, we will use your data to examine to the relationship between training load and athletic performance. You will not be required to engage in any activity outside of what is normally asked of you as part of our athlete monitoring program.

What happens if I say yes, but I change my mind later?

You can leave the research at any time, for any reason, and it will not be held against you. It is important for you to know that you are free to withdraw from this study at any time without penalty. You are free not to answer any questions that you choose or to respond to what is being asked of you without penalty. If you no longer wish to participate in the study, simply notify one of the investigators.

Please note that there may be circumstances under which the investigator may determine that a subject should not continue as a subject. These include long-term injury or illness, failure to comply with the study requirements or withdrawal from the team.

Is there any way being in this study could be bad for me? (Detailed risks)

While every effort will be made to ensure confidentiality, there is the risk of breach of confidentiality.

What happens to the information collected for the research?

We will make every effort to limit the use and disclosure of your personal information, including research study, only to people who have a need to review this information. We cannot promise complete confidentiality. Organizations that may inspect and copy your information include the IRB, Human Research Protection Program, and other authorized representatives of Virginia Tech.

If identifiers are removed from your private information or samples that are collected during this research, that information or those samples could be used for future research studies or distributed to another investigator for future research studies without your additional informed consent.

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Consent to Take Part in a Research Study

The results of this research study may be presented in summary form at conferences, in presentation, reports, academic papers, and as part of a thesis/dissertation.

Can I be removed from the research without my OK?

The person in charge of the research study or the sponsor can remove you from the research study without your approval. Possible reasons for removal include issues during data collection resulting in inaccurate data.

What else do I need to know?

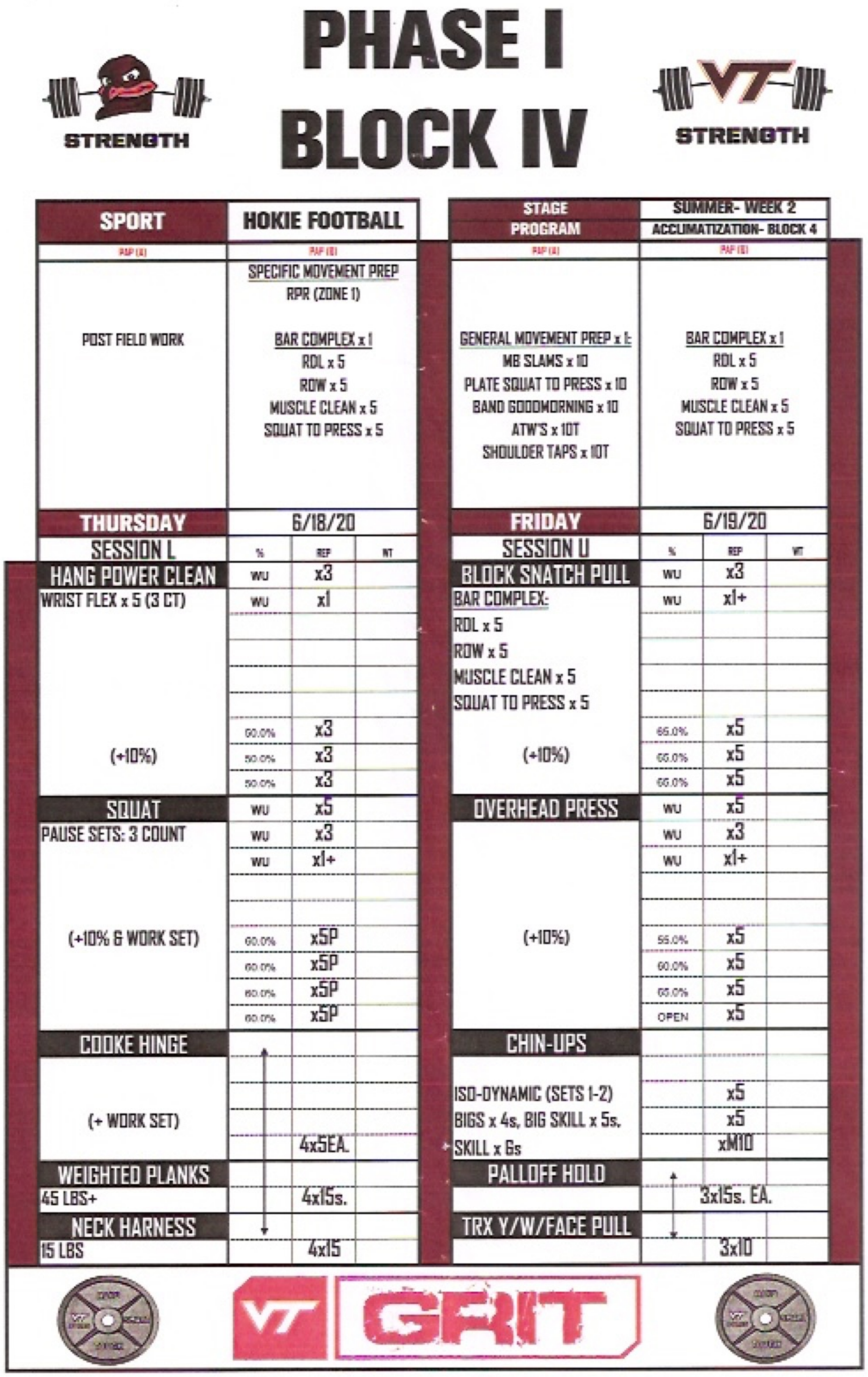
As part of the athlete monitoring program, you are issued a vest (the one already assigned to you). If the vest is misplaced or damaged, we will replace the vest at no charge or penalty to you.

Signature Block for Capable Adult

Your signature documents your permission to take part in this research. We will provide you with a signed copy of this form for your records.

Signature of subject	Date
Printed name of subject	
Signature of person obtaining consent	Date
Printed name of person obtaining consent	

Appendix C – Strength Card Example (Week 2)



PHASE I
BLOCK IV

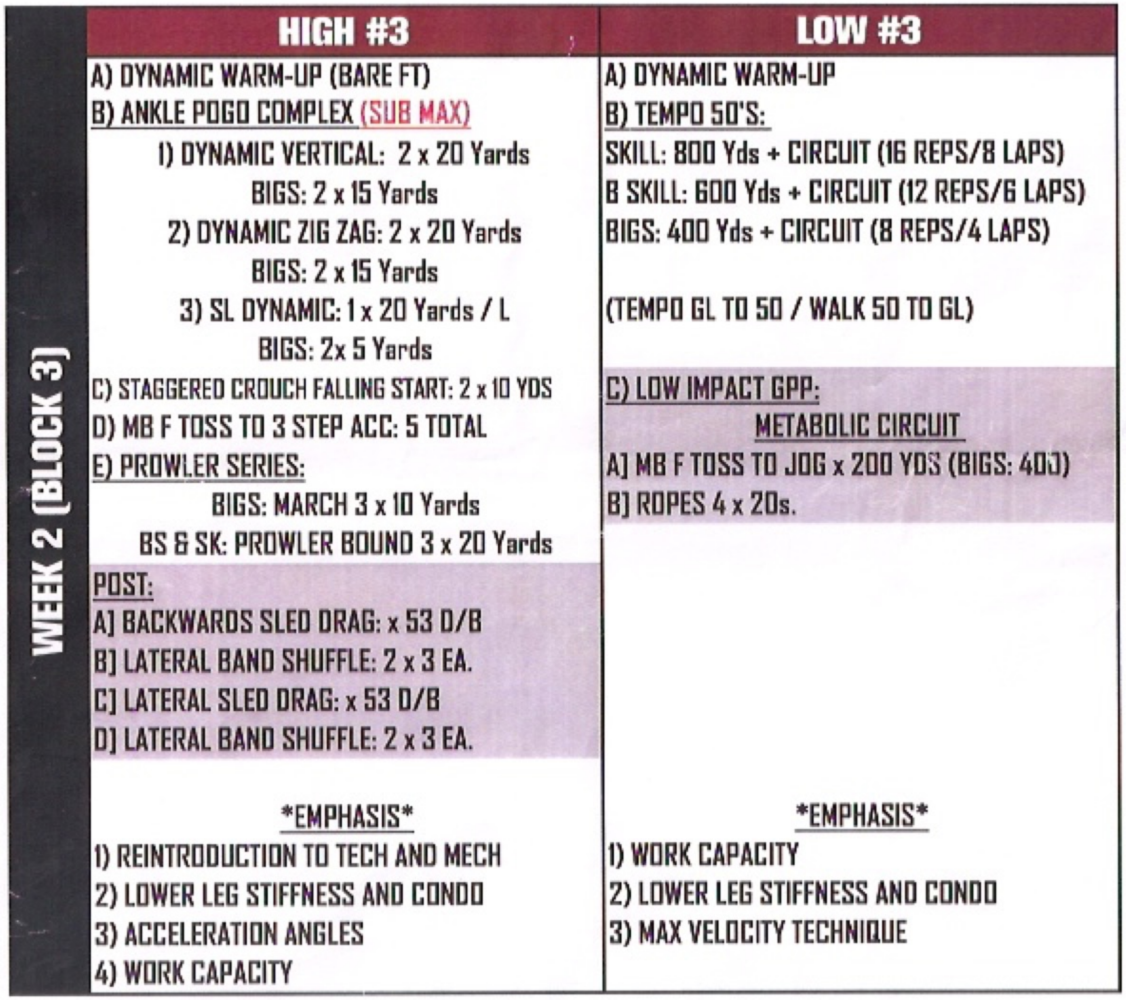
SPORT	HOKIE FOOTBALL
PAP (A)	PAP (B)
POST FIELD WORK	SPECIFIC MOVEMENT PREP RPR (ZONE 1) BAR COMPLEX x 1 RDL x 5 ROW x 5 MUSCLE CLEAN x 5 SQUAT TO PRESS x 5
THURSDAY	6/18/20

SESSION L	%	REP	WT
HANG POWER CLEAN	WU	x3	
WRIST FLEX x 5 (3 CT)	WU	x1	
	60.0%	x3	
(+10%)	50.0%	x3	
	50.0%	x3	
SQUAT	WU	x5	
PAUSE SETS: 3 COUNT	WU	x3	
	WU	x1+	
(+10% & WORK SET)	60.0%	x5P	
	60.0%	x5P	
	60.0%	x5P	
	60.0%	x5P	
COOKE HINGE			
(+ WORK SET)			
		4x5EA.	
WEIGHTED PLANKS			
45 LBS+		4x15s.	
NECK HARNESS			
15 LBS		4x15	

STAGE	SUMMER- WEEK 2
PROGRAM	ACCLIMATIZATION- BLOCK 4
PAP (A)	PAP (B)
GENERAL MOVEMENT PREP x 1: MB SLAMS x 10 PLATE SQUAT TO PRESS x 10 BAND GOODMORNING x 10 ATW'S x 10T SHOULDER TAPS x 10T	BAR COMPLEX x 1 RDL x 5 ROW x 5 MUSCLE CLEAN x 5 SQUAT TO PRESS x 5
FRIDAY	6/19/20

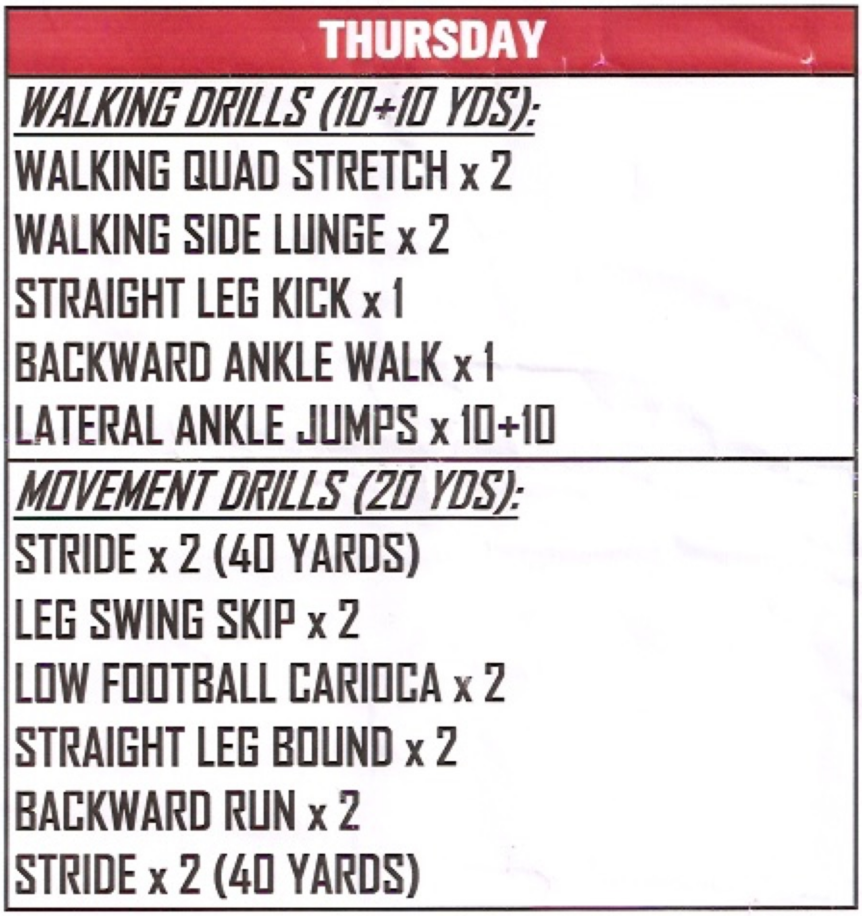
SESSION U	%	REP	WT
BLOCK SNATCH PULL	WU	x3	
BAR COMPLEX:	WU	x1+	
RDL x 5			
ROW x 5			
MUSCLE CLEAN x 5			
SQUAT TO PRESS x 5			
	65.0%	x5	
(+10%)	65.0%	x5	
	65.0%	x5	
OVERHEAD PRESS	WU	x5	
	WU	x3	
	WU	x1+	
(+10%)	55.0%	x5	
	60.0%	x5	
	65.0%	x5	
	OPEN	x5	
CHIN-UPS			
ISO-DYNAMIC (SETS 1-2)		x5	
BIGS x 4s, BIG SKILL x 5s.		x5	
SKILL x 6s		xM10	
PALLOFF HOLD			
		3x15s. EA.	
TRX Y/W/FACE PULL			
		3x10	

Appendix D – Field Work Example (Week 2)



WEEK 2 (BLOCK 3)	HIGH #3	LOW #3
	A) DYNAMIC WARM-UP (BARE FT) B) ANKLE POGO COMPLEX (SUB MAX) 1) DYNAMIC VERTICAL: 2 x 20 Yards BIGS: 2 x 15 Yards 2) DYNAMIC ZIG ZAG: 2 x 20 Yards BIGS: 2 x 15 Yards 3) SL DYNAMIC: 1 x 20 Yards / L BIGS: 2x 5 Yards C) STAGGERED CROUCH FALLING START: 2 x 10 YDS D) MB F TOSS TO 3 STEP ACC: 5 TOTAL E) PROWLER SERIES: BIGS: MARCH 3 x 10 Yards BS & SK: PROWLER BOUND 3 x 20 Yards	A) DYNAMIC WARM-UP B) TEMPO 50'S: SKILL: 800 Yds + CIRCUIT (16 REPS/8 LAPS) B SKILL: 600 Yds + CIRCUIT (12 REPS/6 LAPS) BIGS: 400 Yds + CIRCUIT (8 REPS/4 LAPS) (TEMPO GL TO 50 / WALK 50 TO GL)
	POST: A] BACKWARDS SLED DRAG: x 53 D/B B] LATERAL BAND SHUFFLE: 2 x 3 EA. C] LATERAL SLED DRAG: x 53 D/B D] LATERAL BAND SHUFFLE: 2 x 3 EA.	C) LOW IMPACT GPP: METABOLIC CIRCUIT A] MB F TOSS TO JOG x 200 YDS (BIGS: 400) B] ROPES 4 x 20s.
	EMPHASIS 1) REINTRODUCTION TO TECH AND MECH 2) LOWER LEG STIFFNESS AND CONDO 3) ACCELERATION ANGLES 4) WORK CAPACITY	*EMPHASIS* 1) WORK CAPACITY 2) LOWER LEG STIFFNESS AND CONDO 3) MAX VELOCITY TECHNIQUE

Appendix E – Dynamic Warmup Card



THURSDAY

WALKING DRILLS (10+10 YDS):

WALKING QUAD STRETCH x 2

WALKING SIDE LUNGE x 2

STRAIGHT LEG KICK x 1

BACKWARD ANKLE WALK x 1

LATERAL ANKLE JUMPS x 10+10

MOVEMENT DRILLS (20 YDS):

STRIDE x 2 (40 YARDS)

LEG SWING SKIP x 2

LOW FOOTBALL CARIOCA x 2

STRAIGHT LEG BOUND x 2

BACKWARD RUN x 2

STRIDE x 2 (40 YARDS)

Appendix F – Supplementary Data File – Study #1

Description: The accompanying excel spreadsheet contains the raw data of CMJ performance for study #1.

Filename:

Study #1 GPS Data
- Updated.xlsx

Appendix G – Supplementary Data File – Study #2

Description: The accompanying excel spreadsheet contains the raw data of CMJ performance for study #2.

Filename:

8-Week Training
CMJ Data.xlsx

Appendix H – Supplementary Data File – Study #3

Description: The accompanying excel spreadsheet contains the raw data of CMJ performance for study #2.

Filename:

Acute Fatigue Data
(1).xlsx

Appendix I – Supplementary Data – Energy System Development

Position Group	Average Heart Rate	Heart Rate Exertion	HRE/min
Tuesday and Wednesday Practices			
Wide Receiver	112.4 ± 16.9	147.8 ± 86.1	1.0 ± 0.63
Tight End	115.3 ± 16.8	176.2 ± 80.9	1.3 ± 0.59
Running Back	116.7 ± 16.3	177.0 ± 73.5	1.3 ± 0.53
Offensive Line	119.6 ± 14.9	193.2 ± 92.2	1.4 ± 0.67
Defensive Back	111.6 ± 21.3	146.5 ± 91.1	1.0 ± 0.67
Defensive Line	112.6 ± 11.2	130.7 ± 56.7	0.9 ± 0.41
Linebackers	121.4 ± 16.9	186.7 ± 93.5	1.4 ± 0.68
Off-Season Conditioning			
Wide Receiver	142.3 ± 5.9	181.0 ± 19.8	4.5 ± 0.45
Tight End	152.6 ± 9.4	196.0 ± 22.3	4.9 ± 0.48
Running Back	149.1 ± 10.3	207.8 ± 43.9	5.1 ± 0.95
Offensive Line	162.1 ± 2.8	234.4 ± 30.3	5.8 ± 0.65
Defensive Back	139.6 ± 10.0	172.7 ± 32.9	4.3 ± 0.77
Defensive Line	154.2 ± 7.5	201.5 ± 30.9	5.0 ± 0.72
Linebackers	143.2 ± 7.0	181.8 ± 7.2	4.5 ± 0.14