A Comparison of Tri-Axial Accelerometer Derived Pre-Season, In-Season, and Game Demands in NCAA Division I Football Players

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Abstract

PURPOSE: A tri-axial accelerometer, combined with a magnetometer and gyroscope, can quantify directional movement in three planes of motion. This type of device is often used to measure external workloads (i.e. PlayerLoad^{TM} [PL]) and workload intensity (i.e. PL per minute [PL_{PM}]), during training in collegiate football athletes. This study investigated the percentage of external load contribution by axis (i.e. mediolateral, anteroposterior, and vertical) between seven football positions during summer training, in-season training and games, and within positions between summer training, in-season training and games. **METHODS:** PlayerLoad^{TM} was measured among 59 NCAA Division I football athletes using Catapult Optimeye S5 (13 Defensive Backs [DB], 9 Wide Receivers [WR], 5 Running Backs [RB], 4 Tight Ends [TE], 12 Linebackers [LB], 11 Defensive Linemen [DL], and 6 Offensive Linemen [OL]). PlayerLoad^{TM} per minute was derived by dividing PL by duration. PlayerLoad^{TM} percentages were determined by dividing PL by each PL axis (anteroposterior [PL_{AP}], mediolateral [PL_{ML}], and vertical [PL_{V}]). Linear mixed effects models with random intercepts for player and date were used to assess position specific differences – with respect to percent PL distribution – in the three dimensions. Pairwise differences between positions were not adjusted for multiple comparisons. A linear mixed effect model with random intercepts for player and data was used to assess intra-positional differences from summer training to in-season training. **RESULTS:** Position had an effect on PL, PL_{PM}, and PL distribution during summer training, in-season training and games. Season had a significant effect on percent load distribution within position. The PL_{AP} for all positions, except TE, LB and OL, was significantly higher during summer training, compared to games ($p < 0.001$). The PL_{ML} for all positions was significantly lower during summer training, compared to games ($p < 0.001$). The PL_{V} for all positions, except DL, was significantly higher during summer training ($p < 0.01$). PlayerLoad^{TM} was significantly higher for all positions during in-season training compared to summer training, however, PL_{PM} was significantly lower for all positions. **CONCLUSION:** Both intra-positional, between summer training, in-season training and games, and inter-positional PL, PL_{PM}, and PL distribution differences, by season, were observed. The inter-positional differences are relatively small in absolute terms and may not be meaningful from a positional standpoint. The intra-positional differences suggest that the training done during the summer sessions does not reflect expected in-season training session and game demands. This is especially true of the PL_{ML} axis with summer values ranging 4.02-6.9% lower than game values. The off-season is typically utilized to prepare athletes for the rigor of the in-season. Future studies should examine the demands of the game to select appropriate training loads.

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List of Abbreviations

DB: Defensive back

DL: Defensive lineman

EL: External workload

GPS: Global positioning system

IWT: Integrated wearable technology

LB: Linebacker

OL: Offensive lineman

PL: PlayerLoad^{TM}

PL_{AP}: PlayerLoad^{TM} anteroposterior axis

PL_{ML}: PlayerLoad^{TM} mediolateral axis

PL_{PM}: PlayerLoad^{TM} per minute

PL_{V}: PlayerLoad^{TM} vertical axis

RB: Running back

TE: Tight end

WR: Wide receiver

Chapter 1: Introduction

American football is a field-based team sport characterized by short repeated maximum intensity bouts of effort and extreme collisions, which requires players to possess muscular strength, speed, agility, and muscular power (Fullagar, McCunn, & Murray, 2017; Hoffman, 2008; Wellman, Coad, Goulet, & McLellan, 2016). While the physical demands of American football have historically been based on empirical observations and assumptions (Hoffman, 2008), technological advances have catalyzed quantifying these demands.

External workload (EL) can be described as the total mechanical stress placed on an athlete's body during physical activity (Barrett, Midgley, & Lovell, 2014). Integrated wearable technology (IWT), such as global positioning systems, tri-axial accelerometers, gyroscopes, and magnetometers can provide estimates of EL (Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014; Dellaserra, Gao, & Ransdell, 2014; Ehrmann, Duncan, Sindhusake, Franzsen, & Greene, 2016; Gabbett, 2013; Gabbett, Jenkins, & Abernethy, 2011; Sanders, Roll, & Peacock, 2017; Wellman, Coad, Flynn, Siam, & McLellan, 2017; Wellman, Coad, Goulet, & McLellan, 2015; Wellman et al., 2016). To date, researchers using IWTs have quantified the total distance covered, time spent at various running intensities, maximal speeds, number of accelerative and decelerative efforts at various intensities, number of collisions, and EL in NCAA Division I football athletes (Fullagar et al., 2017; Sanders et al., 2017; Wellman et al., 2017; Wellman et al., 2015, 2016).

Integrated wearable technology is not only used to quantify sport demands, but to monitor EL over time (Boyd, Ball, & Aughey, 2011, 2013; Chambers, Gabbett, Cole, & Beard, 2015; Gabbett et al., 2011; Van Iterson, Fitzgerald, Dietz, Snyder, & Peterson, 2017; Wellman et al., 2015). Longitudinal monitoring of EL helps identify and prevent rapid workload increases, as acute spikes in EL may increase athletes' soft tissue injury risk (Campbell, Bove, Ward, Vargas, & Dolan, 2017; Carey et al., 2017; Gabbett, 2016; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016). The ratio of acute EL, (i.e., the most recent one week), to chronic EL (i.e., the most recent four weeks), has been used in an attempt to estimate non-contact soft tissue injuries (Hulin et al., 2016; Jones, Griffiths, & Mellalieu, 2017; Soligard et al., 2016). Moreover, the acute:chronic workload ratio can be used as a monitoring metric to improve in-season availability (Murray, Gabbett, & Townshend, 2017).

PlayerLoad^{TM} (PL) [Catapult Sports, Melbourne, Australia], the sum of the instantaneous rate of change in acceleration across the three planes of motion (i.e., mediolateral [x], anteroposterior [y], and vertical [z]) obtained from a tri-axial accelerometer, is one of the most popular IWT measures of EL (Casamichana, Castellano, Calleja-Gonzalez, San Román, & Castagna, 2013; Fox, Stanton, & Scanlan, 2018; Gabbett, 2015; Govus, Coutts, Duffield, Murray, & Fullagar, 2018; Murray et al., 2017; Ritchie, Hopkins, Buchheit, Cordy, & Bartlett, 2016; Scanlan, Wen, Tucker, & Dalbo, 2014; Sparks, Coetzee, & Gabbett, 2017; Wellman et al., 2017). Tri-axial accelerometry has been validated as a reliable way to assess mechanical workload in all three planes of motion for multiple team sports (e.g., soccer, rugby, Australian Rules Football, basketball, and ice hockey), including football (Barrett et al., 2014; Boyd et al., 2011, 2013; Campbell et al., 2017; Fox et al., 2018; Gabbett, 2015; Govus et al., 2018; Van Iterson et al., 2017; Wellman et al., 2017).

While PL uses all three planes (x, y, and z) no studies, to date, have examined the three PL components individually in NCAA Division I football athletes. Analyzing the contribution of each separate axis would enhance understanding of sport demands and facilitate more specific programming. Therefore, the primary objective of this study was to analyze and report the various components of PL in a collegiate football season. The specific project aims were to:

(1) Determine if inter-positional differences exist for any of the PL axes, PL, and PL per minute;
(2) Determine if intra-positional differences exist for the aforementioned metrics between summer training, in-season training, and games.

The following chapters will discuss the current state of the literature and the present study's methodology, findings, and conclusions. Chapter two provides an in-depth review of the current literature related to integrated wearable technology, methods used to monitor EL in athletes, and the reliability and validity of the specific technology utilized in this study. Chapter three consists of the methodology of the present study, including information on the study population, procedures, measurement techniques, equipment, and statistical methods. Chapter four describes the results of the study. Comparisons are made of inter- and intra-positional differences of the PL variables, PL, and PL per minute. Chapter five includes a discussion of study results, the significance of the findings, elaborates on limitations, and provides insight into future directions of related research.

Chapter 2: Literature Review

Importance of External Workload

Athlete preparation for the demanding schedule of NCAA Division I football is paramount for team success. Collegiate football players experience several stressors, including training, competition, schoolwork, and social life. Although all these stressors are inevitable, the physical stress from training can be monitored and modulated in order to ensure that the athlete feels ready to perform (Robertson, Bartlett, & Gastin, 2017). Physical stress can be described as the body's external workload (EL), quantified as the amount of mechanical stress placed on the body from all types of movement during physical activity (Barrett et al., 2014; Boyd et al., 2013; Sparks et al., 2017).

Coaches' and researchers' interest in EL analyses have increased for multiple reasons. First, researchers have associated EL to injury risk (Carey et al., 2017; Colby et al., 2014; Fullagar et al., 2017; Gabbett, 2016). Second, EL can help to quantify sport demands and thereby enhance athlete readiness (Bangsbo, Mohr, & Krustrup, 2006; Campbell et al., 2017; Gabbett et al., 2011; Sanders et al., 2017; Van Iterson et al., 2017; Wellman et al., 2015). Athletes that are better prepared to meet the demands of their sport often outperform their peers and counterparts.

External workload measures quantifying American football (and other team sport) demands include total session duration, total distance covered, time spent in various running zones, number of high intensity movement efforts, and PlayerLoad^{TM} (PL). These metrics are most commonly measured via global positioning systems (GPS) or integrated wearable technology (IWT) comprised of a GPS, accelerometer, gyroscope and magnetometer (Gabbett et al., 2011; Sanders et al., 2017; Waldron, Twist, Highton, Worsfold, & Daniels, 2011; Wehbe, Hartwig, & Duncan, 2014; Wellman et al., 2017; Wellman et al., 2015). Only (IWT), by way of accelerometry, can distinguish between all planes of movement (i.e., mediolateral [x], anteroposterior [y], and vertical [z]). By using IWT to examine EL and the derived contribution of each plane of motion, researchers may understand sport demands to a greater degree.

Quantifying External Workload

Multiple EL monitoring techniques have been utilized in the collegiate football setting to determine the mechanical stress placed on an athlete. These methods quantify load using several objective measures that can be used in conjunction with one another. The most widely used measures include, as previously stated, total duration, total distance covered, time spent in various running zones, number of high intensity movement efforts, and PL. Total duration and total distance covered are aggregate measures that provide broad session overviews. They do not explain granular activity during the game nor what type of movements are contributing to the value of total distance. Time spent in running zones (low [0-8 mph], moderate [8-14 mph], moderate-high [>12 mph], and high [>14 mph] speeds) (Sanders et al., 2017) and the number of high intensity movement efforts reveal a more in-depth look into the composition of the total distance and total duration. Specifically, with this information one can estimate a sport's energy system requirements. PlayerLoad^{TM} is an arbitrary unit derived from a tri-axial accelerometer, which is expressed as the instantaneous rate of change in acceleration in the three planes of motion. The PL metric accounts for all movement occurring in each plane of motion, thereby offering greater accuracy into what types of movements are performed in American football.

$$\sum_{i=1}^{n} PlayerLoad = \sqrt{\frac{(ax_i - ax_{i-1})^2 + (ay_i - ay_{i-1})^2 + (az_i - az_{i-1})^2}{100}}$$

Where: a = acceleration,

x = mediolateral,

y = anteroposterior,

z = vertical

Early attempts to examine the collegiate football demands utilized video analysis to look at play lengths and the rest allotted between plays. A study by Iosia and Bishop (2008) showed that the average play lasted 5.23 seconds, whereas the average rest between plays was 36.1 seconds. Offenses with a more run-dominant style ran shorter plays (4.84 seconds) with less rest between plays (35.1 seconds). Pass-dominant styles ran longer lasting plays (5.41 seconds) with more rest between plays (38.1 seconds). Rhea, Hunter, and Hunter (2006) reported similar findings in collegiate football which showed that the average play lasted 5.5 seconds with an average rest of 34 seconds. Additionally, run plays were shorter than passing plays, on average. Hoffman

(2008) reported that approximately fourteen offensive drives occur per game with 4.6 plays per drive. Rhea et al. (2006) reported similar findings of 13.78 ± 2.22 drives per game and 6.26 ± 2.74 plays per drive. This information helps determine competition work to rest ratios so that sport coaches and strength and conditioning coaches may prescribe more specific sessions. Additionally, tracking data over time to determine worst-case scenarios can facilitate team preparation for these situations. However, this information does not reveal individualized player movement on the field, or differences in movement demands between positions.

GPS is used in American collegiate football and other field-based team sports (i.e., soccer, rugby, and Australian Rules Football) to determine total distances covered and time spent in various speed zones between positions (Gabbett, 2015; Gabbett et al., 2011; Jeong, Reilly, Morton, Bae, & Drust, 2011; Murray et al., 2017; Sanders et al., 2017). Sanders et al. (2017) used GPS technology to report average and maximum positional differences of total distance and distance covered at low (0-8 mph), moderate (8-14 mph), moderate-high (>12 mph), and high (>14 mph) speeds. Again, these values do not consider the types of movements performed that comprise the recorded distances. Furthermore, GPS devices are satellite-dependent and therefore restricted to outdoor use. Outdoor recording can be problematic due to environmental interference and the reliance on an adequate number (at least four) of satellites (Scott, Scott, & Kelly, 2016). Scott et al. (2016) showed a negative correlation between the total distance error and the number of satellites signaling the receiver unit. Inter-unit measures were shown to be significantly different during a tight change of direction course (Scott et al., 2016), which is problematic for an intermittent high-intensity field sport such as American football.

Complex analyses utilizing IWT, specifically the tri-axial accelerometer, allow for a more in depth look at what types of movements compose the recorded distances. These data could be used in conjunction with the previously reported running distances to further enhance the training program specificity. However, the three dimensions of PL are necessary to truly ascertain the types of movements being performed during a game (i.e., mediolateral [x], anteroposterior [y], and vertical [z]).

Validity and Reliability of External Workload Measures

Integrating tri-axial accelerometry and GPS data provides practitioners with more information to analyze regarding athletes' movement patterns, work rate, and mechanical loading (Scott et al., 2016). Tri-axial accelerometry has been shown to be reliable in various static and team sport settings (Barrett et al., 2014; Boyd et al., 2011; Nicolella, Torres-Ronda, Saylor, & Schelling, 2018; Scott et al., 2016; Van Iterson et al., 2017). Unlike GPS, accelerometer data do not rely on satellites, so practitioners working with seasonal sports that are played indoors (i.e., basketball, ice hockey, netball, etc.), or have indoor training sessions (i.e., American football, soccer, rugby, etc.), can collect data year-round.

Nedergaard et al. (2017) utilized ground reaction force data – collected from a force platform – to test tri-axial accelerometer validity against whole body center of mass accelerations. Nedergaard et al. (2017) found moderate linear relationships between the accelerometer and whole-body center of mass accelerations for peak acceleration, loading rate, and impulse (R^2 = 0.26, 0.27, and 0.26 respectively) during inline running. However, they found strong linear relationships for peak acceleration and loading rate (R^2 = 0.42 and 0.38, respectively) when cutting at 45 degrees and for peak acceleration, loading rate, and impulse (R^2 = 0.55, 0.36, and 0.59, respectively) when cutting at 90 degrees. Nedergaard et al. (2017) concluded that the practice of utilizing commercial trunk mounted accelerometers is currently the best way to represent whole body center of mass accelerations but should continually improve with increased sampling frequency.

Boyd et al. (2011) showed that accelerometers have good intra- (CV = 1.0%) and inter-unit (CV = 1.10%) reliability during static assessments. The intra- and inter-unit reliability during the dynamic test at 3 Hz was 0.91% and 1.04%, respectively. The intra- and inter-unit reliability during the dynamic test at 8 Hz was 1.05% and 1.02%, respectively. More recently, Nicolella et al. (2018) showed excellent intra-unit reliability for PL of 19 different accelerometers during a dynamic shaker test a 8 Hz for each component of PL – x (Mean CV% ± SD, 0.67 ± 1.33), y (Mean CV% ± SD, 0.74 ± 1.49), and z (Mean CV% ± SD, 0.06 ± 0.02). The devices demonstrated mixed inter-device reliability for PL depending on the acceleration of the shaker and direction of movement.

Present Study

The present study examined how the x, y, and z planes of motion comprised the PL value, and how those values differ both intra- and inter-positionally during pre-season training, in-season training, and during games. Accelerometry allows practitioners to objectively determine the plane that the movement is occurring in. To our knowledge, prior research has not examined the individual components of the PL calculation in collegiate football, or any other sport. It is important to determine the demands of the game from a movement standpoint, streamlining how training time can be effectively utilized during the pre-season and in-season. If discrepancies between types of in-game movements and those completed during pre-season and in-season training are verified in the present study, findings would suggest that training efforts could potentially be focused on targeting more specific game-like qualities.

Chapter 3: Methods

Design

This study is a retrospective data analysis examining the percent of external workload, derived from PlayerLoad^{TM} (PL), distribution by axis (i.e., anteroposterior [PL_{AP}], mediolateral [PL_{ML}], and vertical [PL_{V}]), and workload intensity (PL per minute [PL_{PM}]) among NCAA Division 1 football athletes. PlayerLoad^{TM} is an arbitrary unit of measurement expressed as the sum of the squared instantaneous rate of change in acceleration in each of the three axes (PL_{AP}, PL_{ML} and PL_{V}). The study collection period was split into three phases, 36 summer (June 6, 2016 – July 29, 2016) sessions, 62 in-season (August 5, 2016 – November 25, 2016) sessions, and 12 regular season games (September 1, 2016 – November 26, 2016).

Subjects

Data from 59 NCAA Division I football athletes were used in this study (*n* = 59; defensive back (DB) = 13, wide receiver (WR) = 9, running back (RB) = 4, tight end (TE) = 4, linebacker (LB) = 12, defensive lineman (DL) = 11, and offensive lineman (OL) = 6). The athletes were grouped into their respective positions for inter- and intra-positional comparisons.

Procedures

PlayerLoad^{TM} percentages were determined by dividing each one-dimensional axis of PL (i.e., anteroposterior [PL_{AP}], mediolateral [PL_{ML}], and vertical [PL_{V}]), by the total PL. PlayerLoad^{TM} was measured using Catapult

Optimeye S5 (Catapult Sports, Melbourne, Australia) monitoring systems, an integrated wearable device comprised of a GPS system, tri-axial accelerometer, gyroscope, and magnetometer. Each athlete wore the same unit at each training session, with the unit secured firmly between the scapulae in a neoprene vest undergarment, in accordance with the Optimeye S5's strict manufacturer's guidelines. The Optimeye S5 recorded data at 10 Hz and stored the data internally. During each training session and game, the data are cut and categorized appropriately by session type. After each training session and game, the athletes returned the device, and the data were uploaded to Catapult's OpenField software on a personal computer then exported as a csv file for further analysis in RStudio (version 1.383, RStudio, Inc, Boston, MA). PlayerLoad^{TM} measurements were recorded by the strength and conditioning staff during all training sessions and games. Exclusion criteria from the analysis include the following: 1.) Absence from more than 25% of the total training sessions during summer and in-season; 2.) All N/A values of PL; 3.) PL per minute less than 2.5 standard deviations from the mean; 4.) PL less than 15 arbitrary units; and 5.) Total distance recorded was equal to zero. Catapult Optimeye S5 units were worn during all training sessions and games during the 2016-2017 summer camp and season.

Statistical Analyses

Linear mixed-effects models (Bates, Maechler, Bolker, & Walker, 2015), with random intercepts for player and date, were used to assess whether positions differed with respect to percent player load in the three-dimensional axes, total PL, and PLPM. Positional characteristics were calculated for mean ± standard deviations. Linear mixed-effects models (Bates et al., 2015), with random intercepts for player and date, were also used to assess the magnitude of differences within position with respect to percent PL in the 3-dimensional axes, total PL, and PL_{PM}. These models were conducted to assess differences between summer training and in-season training, summer training and games, and in-season training and games. An ANOVA with a Tukey's HSD test was used to assess demographic differences between positions.

Chapter 4: Results

Table 1 presents the demographic data for each position group. There were no differences in age between positions. Tight ends were significantly taller than all other positions, except OL. Defensive backs and RB were significantly shorter than all other positions, except WR and LB. Offensive linemen were significantly heavier than all other positions.

Table 2 presents the summer training measurements for PL axis percent contribution, PL, and PL_{PM} for each position group. The PL_{AP} for OL was significantly lower than all other positions except TE. There were no significant differences between positions for PL_{ML}. The PL_{V} for TE and OL was significantly higher than LB. Defensive backs and RB had significantly higher PL and PL_{PM} than DL and OL.

Table 3 presents the in-season training measurements for PL axis percent contribution, PL, and PL_{PM} for each position group. The PL_{AP} for DB was significantly higher than OL. The PL_{ML} for OL was higher than all other positions. Defensive linemen had higher PL_{ML} than the remaining positions, except for LB. Linebackers had significantly higher PL_{ML} than both WR and RB. Tight ends had significantly higher PL_{ML} than RB. Wide receivers and running backs had significantly higher PL_{V} than OL. Linebackers, DL, and OL had significantly lower PL and PL_{PM} than DB, WR, and RB. Wide receivers had significantly higher PL and PL_{PM} than all other positions.

Table 4 presents the game measurements for PL axis percent contribution, PL, and PL_{PM} for each position group. The PL_{AP} for DL was significantly lower than all other positions except WR. Tight ends and OL had significantly higher PL_{AP} than WR. There were no differences between positions for PL_{ML}. Defensive linemen had significantly higher PL_{V} than TE, LB, and OL. Tight ends had significantly lower PL_{V} than all other positions, except RB and OL. Defensive backs and WR had significantly higher PL and PL_{PM} than DL.

Table 5 presents the intra-positional differences for PL axis percent contribution, PL, and PL_{PM} between summer and in-season training. Wide receivers, LB, and DL had significantly lower PL_{AP} during in-season training, whereas TE and OL were significantly higher. All positions, except RB, had significantly higher PL_{ML} during in-season training. All positions, except WR and RB, had significantly lower PL_{V} during in-season training. Running backs had significantly higher PL_{V} during in-season training. All positions had significantly higher PL, and lower PL_{PM}, during in-season training.

Table 6 presents the intra-positional differences for PL axis percent contribution and PL between summer training and games. All positions, except TE and OL, had significantly lower PL_{AP} during games. Offensive linemen had higher L_{AP} during games. All positions had significantly higher PL and PL_{ML} during games. All positions had significantly lower PL_{V}, except DL, and lower PL_{PM} during games.

Table 7 presents the intra-positional differences for PL axis percent contribution and PL between in-season training and games. Defensive backs, WR, LB, and DL had significantly lower PL_{AP} during games. All positions, except

OL, had significantly higher PL_{ML} during games. All positions, except DL and OL, had significantly lower PL_{V} during games. Defensive backs, LB, and OL had significantly higher PL during games. All positions had significantly lower PL_{PM} during games.

Chapter 5: Discussion

Summary of Findings

This study had two main objectives: (1) quantify summer, in-season practice, and regular season game loads and load distribution in three axes of motion (i.e., anteroposterior [x], mediolateral [y], and vertical [z]) between football positions; and (2) determine whether load and load distribution differences existed between summer, in-season practices, and regular season games.

Inter-positional differences were compared during the summer training, in-season training, and regular season games. Summer training and games revealed significant inter-positional differences in the PL_{AP} and PL_{V} axes, PL, and PL_{PM}, whereas in-season training revealed differences in all measurements. We did find significant differences between positions, within each season, for each plane of motion. However, these differences were relatively small, with the largest discrepancy occurring during games in the PL_{V} axis between DL, 36%, and TE, 32%. Although significant differences occurred between positions, the general PL axial distribution within position was the same. PL_{ML} had the highest contribution amongst positions regardless of season, and PL_{AP} had the least, in general.

A comparable study in rugby players by Gabbett (2015) showed similar results in Rugby League match play where they examined inter-positional differences in PL and 2D PlayerLoad^{TM} (2DPL) - i.e. the mediolateral and anteroposterior aspects of PL. They identified that forwards' PL and 2DPL, relative to playing time, was significantly higher than all other positions (hookers, adjustables and outside backs). The mediolateral and anteroposterior aspects of PL, determined by the 2DPL, contributed 64% to the overall PL for forwards whereas that contribution was only 60% for adjustables and outside backs. This further illustrates the need for position specific training that simulates match demands.

All intra-positional differences between summer training and regular season games were significant, except for PL_{AP} for TE and PL_{V} for DL. Mean PL values are in contrast with a similar study done by Wellman et al. (2017) in collegiate football players, which examined mean and max PL values during pre-season training camp, in-season practices, and games. In their study, mean PL during the first pre-season week was greater than nearly all in-season values. Also, the cumulative weekly PL for pre-season weeks 1, 2, and 3 were greater than all in-season weeks. Our study revealed that mean PL values, for all positions, were lowest during summer training, which we considered analogous to pre-season camp in the Wellman et al. (2017) study, and highest during games. Differences between our study and those of Wellman et al. (2017) may be due to their smaller sample size (n = 31; DB = 5, WR = 5, RB = 4, TE = 3, LB = 4, DL = 4, OL = 4, and QB = 2) and included an extra position, QB. The present study also extends their findings by examining mean PL at the axes level. Additionally, to our knowledge, no other studies have looked at whether differences in the PL components exist either intra- or inter-positionally.

All positions had significantly ($p < 0.05$) higher PL_{ML} during games than summer training. The PL_{ML} axis is indicative of side to side movements and changes of direction, which are more stressful on the body (Dellal et al., 2010) than anteroposterior or vertical movements. A study by Lu and Chang (2011) revealed that the most efficient gait pattern is to minimize vertical and mediolateral digressions from the body's center of mass. Dellal et al. (2010) showed that intermittent exercise in the form of a shuttle caused greater blood lactate responses and ratings of perceived exertion than simply running inline. The larger responses from intermittent shuttle running can be attributed to the increased amount of changes of direction, given that all other factors were the same. Dellal et al. (2010) showed that the body will have a greater contribution from the anaerobic system when moving in the mediolateral plane. In the present study, games had a higher axial load contribution from PL_{ML} across all positions, ranging from 4.02% - 6.90% greater than summer training. The body is adapting to a summer training stimulus that does not reflect what is required of it during competition.

To adequately prepare an athlete for competition demands, it is imperative that those demands are being mimicked in the training used to prepare the athlete. Training specificity is crucial to elicit sport-specific neuromuscular adaptations (Bompa & Buzzichelli, 2015). As mentioned previously, the game demands are not being addressed during preparation, thus breaking the law of training specificity. Young, McDowell, and Scarlett (2001) further illustrated that movements performed primarily in the anteroposterior plane have little crossover into the mediolateral plane. The authors showed that straight line speed training had no significant impact on improving measures of agility in men. Study subjects were split into a speed training group, an agility training group, and a control group. The speed and agility training groups partook in two training sessions a week for six weeks, whereas the control group did no extra training outside of their usual routine. At the end of the six weeks, the speed training group made significant improvements in only straight sprinting, while the agility training group only showed significant improvements in changes of direction. Another study by Salaj and Markovic (2011) examined the principal components of several jumping, sprinting, and change of direction tests in order to determine if these were connected. Results showed that only tests related to the specific motor ability were correlated and were broken down into four distinct principal components; i.e., sprinting, slow stretch shortening cycle movements (e.g., static and countermovement jumps), changes of direction, and fast stretch shortening cycle movements (e.g., depth jumps and reactive pogo jumps for height). Collectively, these findings necessitate adherence to the laws of specificity when preparing athletes.

PlayerLoad^{TM} per minute is highest during summer training and progressively decreases across in-season training and games, and vice-versa for PL. The widely used periodization model by Matveyev (Verkhoshansky & Siff, 2009) identified that earlier stages of an athlete preparation macrocycle should include a high volume of work accompanied by lower intensity activities. As the season progresses to the competition phase, the relationship between volume and intensity should invert. Our findings are in clear contrast with Matveyev's recommendations, which were designed to enhance sports performance at the time of competition and decrease injury risk (Verkhoshansky & Siff, 2009). The present study's use of accelerometry revealed significant differences from the game demand preparation (i.e. summer and in-season training) to the actual game.

Limitations of the Present Study

This retrospective analysis had inherent limitations. Participation criterion were not set prior to the data collection, which can lead to selection bias. Unlike Wellman et al. (2017), the summer training was not separated into the three pre-season camps, nor was the in-season training into daily components. Dividing the data into its seasonal subcomponents may allow for a more in-depth analysis into how training is periodized on a weekly and monthly basis. Although S and CB, RB and fullbacks, tackles, guards and centers, defensive ends and defensive tackles, have similar roles, they are technically separate positions but were classified as one, DB, RB, OL, and DL respectively, in order to increase positional sample size. PL values did not account for playing time as in the study by Gabbett (2015). Finally, the present study population is representative of only one team competing in NCAA Division I football. These findings may not be characteristic of other coaching philosophies.

Conclusion

Intra-positional differences exist between summer training, in-season training, and games. These differences suggest a disconnect between the training used in preparation of competition, and competition itself. Movements in the mediolateral plane have the highest contribution to the total PL value. Targeted conditioning focusing on game demands could lead to enhanced movement efficiency. Future research should further analyze the positional demands of the game by movement axis to make more specific training recommendations. Future studies should also include more teams to identify if coaching philosophy has a profound impact on the movements that the athletes undertake.

Table 1: Cohort Demographics and Anthropometric Characteristics

	DB *n* = 13	WR *n* = 9	RB *n* = 4	TE *n* = 4	LB *n* = 12	DL *n* = 11	OL *n* = 6
Age (years)	19.24^{a} (1.35)	19.22^{a} (0.93)	20.36^{a} (1.08)	20.26^{a} (0.88)	19.41^{a} (1.29)	19.93^{a} (1.33)	21.18^{a} (1.76)
Height (inches)	71.10^{d} (1.86)	73.58^{cd} (1.66)	70.86^{d} (0.87)	77.91^{a} (2.83)	72.94^{cd} (1.48)	74.19^{bc} (1.51)	76.18^{ab} (1.85)
Weight (pounds)	196.09^{d} (10.46)	203.53^{d} (11.16)	217.48^{cd} (14.14)	249.98^{bc} (13.21)	230.09^{c} (9.56)	269.84^{b} (33.06)	319.88^{a} (11.96)

Reported as mean (± standard deviation). Shared letter within row indicates no significant (p = 0.05) difference). (DB = Defensive Back; WR = Wide Receiver; RB = Running Back; TE = Tight End; LB = Linebacker; DL = Defensive Line; OL = Offensive Line)

Table 2: Summer Training PlayerLoad^{TM} Percent Distribution and PlayerLoad^{TM} Differences between Positions

	DB *n* = 13	WR *n* = 9	RB *n* = 4	TE *n* = 4	LB *n* = 12	DL *n* = 11	OL *n* = 6
PL_{AP} (% AU)	24.25^{a} (0.56)	24.81^{a} (0.66)	24.95^{a} (0.97)	23.24^{ab} (0.98)	24.94^{a} (0.58)	23.91^{a} (0.60)	21.40^{b} (0.80)
PL_{ML} (% AU)	38.70^{a} (0.50)	37.88^{a} (0.60)	38.32^{a} (0.88)	37.65^{a} (0.89)	38.76^{a} (0.53)	39.20^{a} (0.55)	39.57^{a} (0.72)
PL_{V} (% AU)	37.05^{ab} (0.68)	37.31^{ab} (0.80)	36.73^{ab} (1.19)	39.11^{a} (1.20)	36.29^{b} (0.70)	36.89^{ab} (0.73)	39.02^{a} (0.98)
PlayerLoad^{TM} (AU)	244.62^{a} (15.32)	242.37^{a} (16.19)	236.20^{ab} (14.21)	215.12^{ab} (19.32)	226.18^{ab} (15.50)	216.06^{b} (15.68)	200.39^{b} (17.45)
PL_{PM} (AU)	5.16^{a} (0.23)	5.12^{a} (0.26)	4.99^{ab} (0.34)	4.52^{ab} (0.34)	4.74^{ab} (0.24)	4.55^{b} (0.24)	4.28^{b} (0.29)

Reported as mean (± standard deviation). Shared letter within row indicates no significant (p = 0.05) difference. (PL_{AP} = Anteroposterior Axis; PL_{ML} = Mediolateral Axis; PL_{V} = Vertical Axis; PL_{PM} = PlayerLoad^{TM} Per Minute; DB = Defensive Back; WR = Wide Receiver; RB = Running Back; TE = Tight End; LB = Linebacker; DL = Defensive Line; OL = Offensive Line)

Table 3: In-Season Training PlayerLoad^{TM} Percent Distribution and PlayerLoad^{TM} Differences between Positions

	DB *n* = 13	WR *n* = 9	RB *n* = 4	TE *n* = 4	LB *n* = 12	DL *n* = 11	OL *n* = 6
PL_{AP} (% AU)	24.09^{a} (0.50)	23.54^{ab} (0.59)	24.52^{ab} (0.87)	23.86^{ab} (0.87)	24.07^{ab} (0.52)	22.81^{ab} (0.54)	22.35^{b} (0.72)
PL_{ML} (% AU)	39.76^{abc} (0.38)	39.57^{a} (0.44)	38.19^{b} (0.64)	40.03^{ac} (0.64)	40.74^{cd} (0.39)	41.74^{d} (0.41)	43.45^{e} (0.53)
PL_{V} (% AU)	36.17^{ab} (0.59)	36.91^{a} (0.71)	37.32^{a} (1.05)	36.14^{ab} (1.05)	35.20^{ab} (0.61)	35.49^{ab} (0.64)	34.25^{b} (0.87)
PlayerLoad^{TM} (AU)	355.26^{a} (14.22)	396.75^{b} (15.99)	332.79^{ac} (17.69)	296.51^{cd} (19.70)	285.34^{d} (14.58)	268.14^{d} (14.97)	247.40^{d} (19.79)
PL_{PM} (AU)	3.55^{a} (0.11)	3.98^{b} (0.14)	3.34^{ac} (0.20)	3.00^{cd} (0.20)	2.86^{de} (0.12)	2.67^{de} (0.12)	2.48^{e} (0.17)

Reported as mean (± standard deviation). Shared letter within row indicates no significant (*p* = 0.05) difference. (PL_{AP} = Anteroposterior Axis; PL_{ML} = Mediolateral Axis; PL_{V} = Vertical Axis; PL_{PM} = PlayerLoad^{TM} Per Minute; DB = Defensive Back; WR = Wide Receiver; RB = Running Back; TE = Tight End; LB = Linebacker; DL = Defensive Line; OL = Offensive Line)

Table 4: Game PlayerLoad^{TM} Percent Distribution and PlayerLoad^{TM} Differences between Positions

	DB *n* = 13	WR *n* = 9	RB *n* = 4	TE *n* = 4	LB *n* = 12	DL *n* = 11	OL *n* = 6
PL_{AP} (% AU)	21.92^{ab} (0.57)	20.48^{ac} (0.69)	22.89^{ab} (1.03)	23.04^{b} (1.03)	22.29^{ab} (0.60)	20.06^{c} (0.62)	22.89^{b} (0.83)
PL_{ML} (% AU)	42.91^{a} (0.58)	43.64^{a} (0.69)	42.85^{a} (1.02)	45.03^{a} (1.01)	43.25^{a} (0.62)	43.68^{a} (0.63)	44.19^{a} (0.82)
PL_{V} (% AU)	35.15^{ac} (0.57)	35.89^{ac} (0.68)	34.18^{abc} (0.99)	31.92^{b} (0.98)	34.46^{ad} (0.61)	36.23^{c} (0.62)	32.90^{bd} (0.80)
PlayerLoad^{TM} (AU)	443.99^{a} (39.29)	428.36^{a} (46.15)	331.17^{ab} (66.77)	334.23^{ab} (66.44)	391.19^{ab} (41.35)	294.03^{b} (42.48)	384.16^{ab} (54.73)
PL_{PM} (AU)	2.24^{a} (0.18)	2.15^{a} (0.22)	1.69^{ab} (0.33)	1.72^{ab} (0.33)	2.00^{ab} (0.19)	1.51^{b} (0.20)	1.94^{ab} (0.27)

Reported as mean (± standard deviation). Shared letter within row indicates no significant (p = 0.05) difference. (PL_{AP} = Anteroposterior Axis; PL_{ML} = Mediolateral Axis; PL_{V} = Vertical Axis; PL_{PM} = PlayerLoad^{TM} Per Minute; DB = Defensive Back; WR = Wide Receiver; RB = Running Back; TE = Tight End; LB = Linebacker; DL = Defensive Line; OL = Offensive Line)

Table 5: Summer Training to In-Season Training Percent Load Differences Within Position by Axis

	DB *n* = 13	WR *n* = 9	RB *n* = 4	TE *n* = 4	LB *n* = 12	DL *n* = 11	OL *n* = 6
PL_{AP} (% AU)	-0.10 (0.36)	-1.26 (0.34) ***	-0.59 (0.39)	+0.95 (0.32) **	-0.72 (0.30) *	-1.12 (0.38) **	+1.13 (0.29) ***
PL_{ML} (% AU)	+1.10 (0.29) ***	+1.60 (0.31) ***	-0.22 (0.33)	+2.33 (0.31) ***	+2.21 (0.29) ***	+2.70 (0.28) ***	+3.79 (0.29) ***
PL_{V} (% AU)	-1.00 (0.31) **	-0.36 (0.29)	+0.82 (0.38) *	-3.28 (0.44) ***	-1.55 (0.25) ***	-1.59 (0.38) ***	-4.89 (0.48) ***
PlayerLoad^{TM} (AU)	+110.35 (17.85) ***	+159.43 (18.14) ***	+97.86 (16.25) ***	+93.50 (16.11) ***	+56.62 (16.21) **	+52.26 (15.59) **	+56.80 (14.24) ***
PL_{PM} (AU)	-1.65 (0.14) ***	-1.10 (0.14) ***	-1.66 (0.15) ***	-1.40 (0.16) ***	-2.00 (0.16) ***	-1.88 (0.15) ***	-1.78 (0.18) ***

Reported as mean (± standard deviation). * Indicates $p < 0.05$. ** Indicates $p < 0.01$. *** Indicates $p < 0.001$. (PL_{AP} = Anteroposterior Axis; PL_{ML} = Mediolateral Axis; PL_{V} = Vertical Axis; PL_{PM} = PlayerLoad^{TM} Per Minute; DB = Defensive Back; WR = Wide Receiver; RB = Running Back; TE = Tight End; LB = Linebacker; DL = Defensive Line; OL = Offensive Line)

Table 6: Summer Training to Game Percent Load Differences Within Position by Axis

	DB *n* = 13	WR *n* = 9	RB *n* = 4	TE *n* = 4	LB *n* = 12	DL *n* = 11	OL *n* = 6
PL_{AP} (% AU)	-2.08 (0.53) ***	-4.23 (0.53) ***	-1.35 (0.63) *	+0.45 (0.49)	-2.51 (0.46) ***	-4.02 (0.56) ***	+1.53 (0.42) ***
PL_{ML} (% AU)	+4.02 (0.43) ***	+5.60 (0.48) ***	+4.24 (0.52) ***	+6.90 (0.49) ***	+4.79 (0.44) ***	+4.80 (0.42) ***	+4.30 (0.41) ***
PL_{V} (% AU)	-1.93 (0.47) ***	-1.39 (0.46) **	-2.95 (0.62) ***	-7.42 (0.67) ***	-2.32 (0.40) ***	-0.77 (0.56)	-5.83 (0.70) ***
PlayerLoad^{TM} (AU)	+209.10 (26.98) ***	+195.56 (28.42) ***	+124.20 (25.04) ***	+118.48 (24.72) ***	+185.05 (24.86) ***	+82.83 (23.42) ***	+174.54 (22.01) ***
PL_{PM} (AU)	-2.91 (0.20) ***	-2.97 (0.21) ***	-3.19 (0.22) ***	-2.74 (0.24) ***	-2.77 (0.23) ***	-3.07 (0.22) ***	-2.45 (0.25) ***

Reported as mean (± standard deviation). * Indicates $p < 0.05$. ** Indicates $p < 0.01$. *** Indicates $p < 0.001$. (PL_{AP} = Anteroposterior Axis; PL_{ML} = Mediolateral Axis; PL_{V} = Vertical Axis; PL_{PM} = PlayerLoad^{TM} Per Minute; DB = Defensive Back; WR = Wide Receiver; RB = Running Back; TE = Tight End; LB = Linebacker; DL = Defensive Line; OL = Offensive Line)

Table 7: In-Season Training to Game Percent Load Differences Within Position by Axis

	DB *n* = 13	WR *n* = 9	RB *n* = 4	TE *n* = 4	LB *n* = 12	DL *n* = 11	OL *n* = 6
PL_{AP} (% AU)	-1.97 (0.50) ***	-2.98 (0.50) ***	-0.77 (0.61)	-0.43 (0.47)	-1.77 (0.43) ***	-2.91 (0.53) ***	+0.42 (0.40)
PL_{ML} (% AU)	+2.90 (0.41) ***	+4.02 (0.46) ***	+4.48 (0.50) ***	+4.60 (0.47) ***	+2.56 (0.42) ***	+2.12 (0.40) ***	+0.46 (0.39)
PL_{V} (% AU)	-0.93 (0.45) *	-1.04 (0.44) *	-3.77 (0.60) ***	-4.17 (0.64) ***	-0.77 (0.38) *	+0.81 (0.53)	-0.89 (0.66)
PlayerLoad^{TM} (AU)	+98.45 (25.27) ***	+33.52 (27.20)	+25.32 (23.97)	+26.50 (23.67)	+129.07 (23.73) ***	+29.54 (22.38)	+115.17 (20.88) ***
PL_{PM} (AU)	-1.27 (0.19) ***	-1.88 (0.20) ***	-1.54 (0.21) ***	-1.33 (0.23) ***	-0.77 (0.22) ***	-1.20 (0.21) ***	-0.69 (0.24) **

Reported as mean (± standard deviation). * Indicates $p < 0.05$. ** Indicates $p < 0.01$. *** Indicates $p < 0.001$. (PL_{AP} = Anteroposterior Axis; PL_{ML} = Mediolateral Axis; PL_{V} = Vertical Axis; PL_{PM} = PlayerLoad^{TM} Per Minute; DB = Defensive Back; WR = Wide Receiver; RB = Running Back; TE = Tight End; LB = Linebacker; DL = Defensive Line; OL = Offensive Line)

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