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IMPACT OF PRACTICE TRAINING LOADS ON NEUROMUSCULAR AND PERCEPTUAL FATIGUE DURING AN NCAA DIVISION III COLLEGIATE FOOTBALL SEASON

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IMPACT OF PRACTICE TRAINING LOADS ON NEUROMUSCULAR AND PERCEPTUAL FATIGUE DURING AN NCAA DIVISION III COLLEGIATE FOOTBALL SEASON

By John M. Schimenz

We recommend acceptance of this thesis in partial fulfillment of the candidate's requirements for the degree of Master of Science in Human Performance (Applied Sport Science Emphasis).

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ABSTRACT

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PURPOSE**:** This study examined neuromuscular fatigue management from a daily undulating practice periodization plan during an NCAA Division III collegiate football season. METHODS**:** Thirty university football players participated in this study during the first seven weeks of the competition season. Triaxial accelerometers were worn at every practice to track mechanical load. Neuromuscular fatigue was assessed through loaded countermovement jump and perceptual fatigue from wellness variables on Monday, Wednesday, and Friday mornings. One-way analyses of variance with repeated measures determined significant differences between days in all variables, and Cohen's d determined effect sizes. RESULTS**:** Significant differences in mechanical load were identified between all days of the practice week. All jump variables had trivial to small improvements from Monday to Friday. Perceptions of fatigue, soreness, and overall well-being showed moderate to large negative effect sizes from Monday to Wednesday; however, these values improved from Wednesday to Friday so that Friday had trivial or small negative effect sizes when compared to Monday. CONCLUSION**:** Neuromuscular and perceptual fatigue were successfully managed throughout the practice week.

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INTRODUCTION

American football is a collision team sport that requires its players to perform athletic movements requiring a high level of strength, power, speed, and changes of direction performed repeatedly at high intensities (Ward, Ramsden, Coutts, Hulton, & Drust, 2018). To prepare for these physical demands, teams practice between games, performing various drills and exercises based on each position group's responsibilities (Ward et al., 2018). These practice sessions must be strenuous enough to maintain sport-specific fitness, but not too strenuous so that recovery from neuromuscular fatigue (NMF) can occur before the next game (Wellman, Coad, Flynn, Siam, & McLellan, 2019a). If not accounted for, residual NMF may have a detrimental impact on sport performance (McLean, Coutts, Kelly, McGuigan, & Cormack, 2010). Therefore, it is important to monitor and manage external training loads, or the volume and intensity of physical activity accumulated at practices, as they give an indication of the mechanical stresses on the musculoskeletal system, which in turn impact NMF (Vanrenterghem, Nedergaard, Robinson, & Drust, 2017).

Proper periodization of external training loads is critical during the in-season in order to manage NMF effectively between games. Few published studies have detailed the periodization plan for football teams across each week of practice, but those that have indicate that the highest external training loads tend to be three days post-competition, decreasing every subsequent practice until the next game (Ward et al., 2018; Wellman et al., 2019a). A progressive increase or decrease in training loads, termed “linear” periodization plan, is in contrast to an “undulating” periodization plan, where the training loads alternate between high and low values (Rhea, Ball, Phillips, & Burkett, 2002). Comparing both periodization methods, it is well established that a daily undulating strength training program produces similar (Ullrich, Pelzer, Oliveira, & Pfeiffer, 2016) or greater improvements (Miranda et al., 2011; Rhea et al., 2002) in strength compared to a linear program. Thus, football coaches may benefit from adopting an undulating program when planning their weekly practice schedules to effectively manage NMF.

To quantify external training loads at practices, team sports have utilized triaxial accelerometers (TA) (Sanders, Roll, Peacock, & Kollock, 2018; Ward et al., 2018; Wellman et al., 2019a). Shown to be both valid and reliable (Johnstone et al., 2012), TAs monitor the number and intensities of gravitational forces (g-forces) accumulated from sprints, jumps, changes in direction, as well as collisions from blocking and tackling (Sanders et al., 2018; Ward et al., 2018). Due to the unreliability in global positioning systems’ position readings by at least 5 meters (Duncan et al., 2012), and since many football actions occur within a 5-meter distance (e.g. blocking) (Rhea, Hunter, & Hunter, 2006), TAs may be the preferred hardware option to monitor external training loads in collision team sports (Cardinale & Varley, 2017).

The NMF accumulated from training loads can be monitored using objective tests such as the countermovement vertical jump (CMJ), which has widely been used to monitor levels of NMF across days and/or weeks, both in unloaded (Cormack, Newton, & McGuigan, 2008; Gathercole, Sporer, Stellingworth, & Sleivert, 2015; McLean et al., 2010; Rowell, Aughey, Hopkins, Steward, & Cormack, 2017) and loaded conditions

(Hills & Rogerson, 2018). Several CMJ variables have been found to be sensitive to NMF, including jump height, mean power relative to bodyweight, and peak velocity (Cormack et al., 2008; Gathercole et al., 2015; Rowell et al., 2017). In addition, CMJ movement strategy has been shown to change in the presence of NMF, so variables that incorporate the eccentric phase of the jump are also important to consider (Legg, Pyne, Semple, and Ball, 2017; Schmitz, Cone, Copple, Henson, & Schultz, 2014).

Likewise, subjective wellness questionnaires are commonly used in sports to monitor athletes' readiness to train/compete, usually analyzing a variety of different variables, such as perceptions of fatigue, general muscle soreness, sleep quality, stress, mood, and overall well-being (McLean et al., 2010; McLean, Petrucelli, & Coyle, 2012; Wellman, Coad, Flynn, Climstein, & McLellan, 2017). Unlike performance testing, which may be time-consuming and possibly fatigue inducing, wellness questionnaires are quick, inexpensive, and easy to administer (Main & Grove, 2009) which makes them useful for monitoring NMF.

To our knowledge, there have been no studies that have utilized a daily undulating periodization plan in American football and tracked its impact on NMF throughout a week of practices. Therefore, the purpose of this research was to examine NMF management through CMJ performance and wellness scores using a daily undulating mechanical load over the practice week during the first half of the competitive season. We hypothesized that fatigue produced by high training loads early in the week would subside by the end of the practice week due to the undulation of training load from Monday to Friday.

METHODS

Experimental Approach to the Problem

This observational study examined the changes in CMJ performance and wellness responses that represent changes in fatigue over the practice week through the first six games (Weeks 1-3, 5-7) of the 2018-2019 National Collegiate Athletic Association (NCAA) Division III collegiate football's competition season. Mechanical training load (ML) data was collected from 30 practice sessions (Monday through Friday) using valid and reliable TAs (Johnstone et al., 2012). Jump performance data was collected from three jump testing sessions per week (Monday, Wednesday, and Friday) to determine NM responses due to the total practice training load. In addition, a questionnaire regarding each player's subjective feelings of wellness was completed immediately prior to the jump performance testing. Players were familiarized with all testing during the last two weeks of preseason practices before the first competition week. Two strength training sessions (Tuesday and Thursday) and one competition (Saturday) occurred each week. Training loads during strength training sessions and football games were not monitored.

Players

Thirty NCAA Division III American football players (age, 20.5 ± 1.4 years; collegiate football experience, 1.7 ± 1.1 years; height, 182.9 ± 7.6 cm; body mass, 101.4 ± 15.6 kg) from the University of Wisconsin-La Crosse volunteered to participate in this study. Prior to the season, the football coaching staff selected five players per position (wide receivers, defensive backs, offensive linemen, defensive linemen, offensive backs/tight ends, and linebackers) who were expected to receive a significant amount of playing time during the season to be monitored during practices. In addition, before the start of the study, all players were given a written and verbal description of the study and possible risks, and they signed a voluntary written consent form that was approved by the university's institutional review board (Appendix A).

Procedures

Sport Practice

All practice sessions started at the same time in the afternoon. The average total duration for each practice was 93.0 ± 41.6 minutes, ranging from 45 - 135 minutes. The players' physical activity during each practice session was monitored using TAs (Bioharness; Zephyr Technology, Annapolis, United States of America) sampling at 100 Hz. These devices were strapped across the middle of each player's chest at the level of the xiphoid process with the device at approximately the left mid-axillary line. The devices were turned on as soon as the players stepped onto the practice field and turned off within 1 minute after the last drill at the end of practice. The devices recorded individual mechanical intensity and ML at each practice. Mechanical intensity is the peak g-force value within all three dimensions taken over the course of each second sampled at 100 Hz (arbitrary units, a.u.). The peak g-force value is assigned a value on a linear scale of 0 - 10, where 0.5 g-forces equals 0, and > 6.0 g-forces equals 10. The sum of all mechanical intensities is ML (see Equation 1).

$$\text{Mechanical Load} = \sum_{e=1}^{n}(\text{Mechanical Intensity} * \text{Number of Seconds}) \quad (1)$$

As agreed upon by the coaches and researchers before the commencement of the study, a daily undulating periodization plan was implemented, with a goal ML range for each day. The total weekly ML goal during in-season practice was determined by first finding the average daily ML over the last 7 days of training camp. The seven-day average was multiplied by 5 practice days, and 90% of that product was used to determine the total weekly ML goal. Then, the periodization percentages were used to calculate the ML goal for each practice (Table 1).

7-Day Training Camp Average	Total Weekly ML Goal	Monday 15 – 20%	Tuesday 25 – 30%	Wednesday 10 – 12%	Thursday 25 – 30%	Friday 10 – 15%
76	342	52 – 69	87 – 104	35 – 42	87 – 104	35 - 52

Table 1. Mechanical load (ML) periodization plan (a.u.).

After each practice, ML and mechanical intensity data were uploaded to the OmniSense™ 5.0 Software System (Zephyr Technology, Annapolis, United States of America) on a laptop computer and saved into individual files for each player. Data for each player was reported to the head football coach and the offensive and defensive coordinators within one hour after practice was completed to assist in planning the next day's practice. Hydration and nutritional status were not monitored as part of this study.

Jump Testing

All players performed CMJ testing at approximately the same time of day (10 am - 12 pm) each Monday, Wednesday, and Friday. Players reported to the Human Performance Lab and completed a standardized warm-up consisting of 5 minutes of stationary cycling (100 - 120 W) followed by seven specified dynamic stretching and mobility exercises for the lower body. After that, prior to jumping, the players were weighed on a digital scale (± 0.01 kg) (Rice Lake Weighing Systems, Rice Lake, WI).

On a Smith machine (Plyopower Technologies, Lismore, Australia), with 20 kg loaded on their shoulders in a high-bar position, two sets of three CMJs were performed, with a minimum of 20 seconds of rest between reps and a minimum of 1 minute of rest between sets (Gathercole et al., 2015; Hills & Rogerson, 2018). The loaded CMJ started with the player in the tall standing position with feet flat. The player descended into the squat position to a self-selected depth and immediately jumped up as high as possible while keeping the bar on his shoulders. If at any point the bar came off the shoulders, the jump was not scored and was repeated. A valid and reliable linear position transducer (GymAware; Kinetic Performance Technologies, Canberra, Australia) attached to the top of the Smith machine rack determined mean power relative to body mass, peak velocity, jump height, and dip (eccentric displacement) (Dorrell, Moore, Smith, & Gee, 2019).

Wellness Questionnaire

Before the players performed jump testing, they completed a wellness questionnaire (Appendix B) previously used with research in collegiate football (Wellman et al., 2017; Wellman, Coad, Flynn, Siam, & McLellan, 2019b) and other team sports (McLean et al., 2010; McLean et al., 2012). This questionnaire assessed five factors of wellness, including perceptions of fatigue, sleep quality, general muscle soreness, stress, and mood on a five-point scale (scores of 1 to 5, 0.5-point increments; 1 = least favorable, 3 = normal, 5 = most favorable). Overall well-being was another factor of wellness determined by averaging all wellness scores for each player by day.

Statistical Analyses

Data were analyzed in two different groups. For Group A, player data were used if there was no missing data (i.e. missed practice, jumping session, or wellness scores) within each week. Therefore, Group A included 30 players in Week 1, 23 in Week 2, 27 in Week 3, 26 in Week 5, 17 in Week 6, and 24 in Week 7, equating to an equal number of observations (n = 147) between days. In Group B, player data were included if there was no missing data throughout the course of the study. Thus, 13 of the original 30 players comprised Group B, resulting in a fewer number of observations (n = 78) between days. Comparisons were made within each group, but inter-group comparisons were not analyzed due to the violations of independence between groups (Devore & Peck, 2001). However, both groups were reported in order to show the similarity of results in the two models of analysis.

One-way analyses of variance with repeated measures were employed to determine differences in ML, CMJ, and wellness variables between collection days, with scores presented as mean ± SD. The assumption of normality was assessed through visual inspection of Q-Q plots of standardized residuals, and Mauchly's test was performed to assess the assumption of sphericity. A Greenhouse-Geiser correction was utilized for interpretation when sphericity was violated. When significant differences were identified at an alpha level of 0.05, a post hoc Bonferroni test was used to explore where the differences existed. The magnitude of the differences between days were quantified by effect size using Cohen's d, with the following classifications: trivial ($-0.20 < d < 0.20$), small ($-0.50 < d \leq -0.20$ or $0.20 \leq d < 0.50$), moderate ($-0.80 < d \leq -0.50$ or $0.50 \leq d < 0.80$), and large ($d \leq -0.80$ or $d \geq 0.80$) (Cohen, 1992). All statistical analysis was performed using software (Statistical Package for Social Sciences Version 25; International Business Machines, Armonk, United States of America).

RESULTS

Mechanical Load

From day to day, the ML alternated between high and low values (Figure 1) and were found to be significantly different from one another between all days of the week ($p < 0.001$). In Group A, the highest ML was on Tuesday. Effect sizes indicate the difference in ML between Tuesday and all other days of the week was large ($d = 1.20 – 3.59$), except when compared to Thursday, where the difference was small ($d = 0.46$). Furthermore, Thursday load was significantly higher than Wednesday ($p < 0.001$, $d = 2.12$) and Friday ($p < 0.001$, $d = 2.68$), but only moderately higher than Monday ($p < 0.001$, $d = 0.73$). Mechanical load for Monday was higher than both Wednesday ($p < 0.001$, $d = 1.13$) and Friday ($p < 0.001$, 1.57), and Wednesday was higher than Friday ($p < 0.001$, $d = 0.61$). Similar results were observed in Group B. Mechanical load was significantly higher on Tuesday than all other days of the week ($p < 0.001$). Effect sizes indicate that these differences were large ($d = 1.30 - 3.67$), except for Thursday, where a small difference was observed ($p < 0.001$, $d = 0.49$). Thursday was significantly larger than Monday ($p < 0.001$, $d = 0.81$), Wednesday ($p < 0.001$, $d = 2.15$), and Friday ($p < 0.001$, $d =2.70$). Monday ML was higher than Wednesday ($p < 0.001$, $d = 0.94$) and Friday ($p < 0.001$, $d = 1.37$), and Wednesday was higher than Friday ($p < 0.001$, $d = 0.67$).

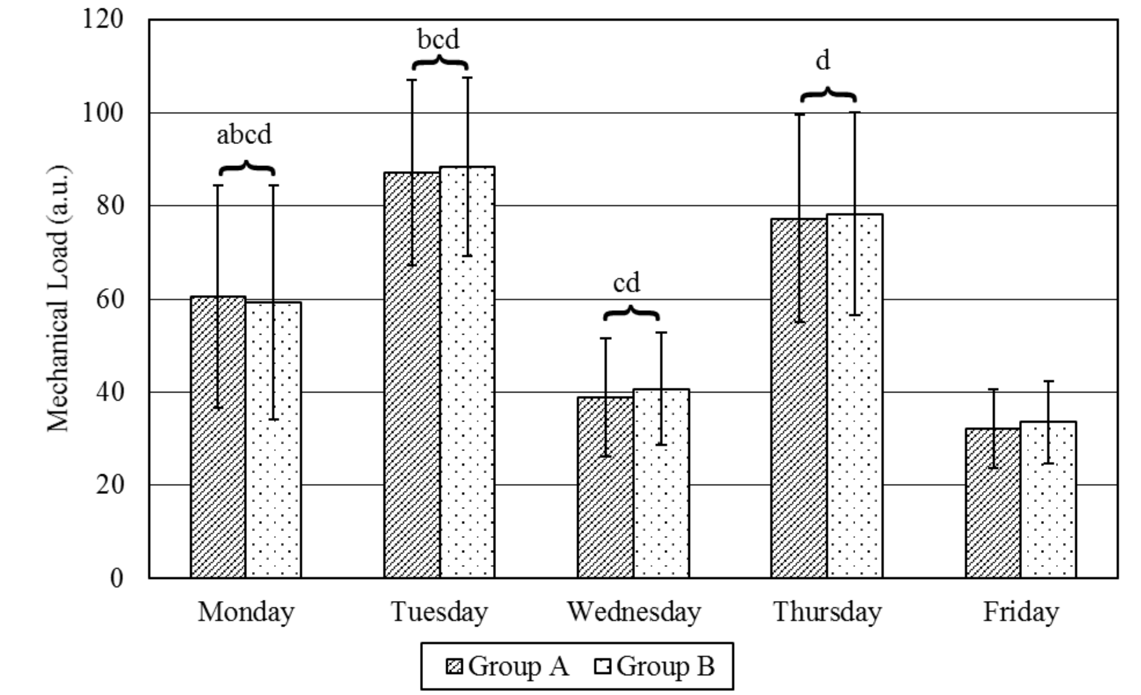

Figure 1. Mechanical load (a.u., mean ± SD). Significantly different than [a]Tuesday, [b]Wednesday, [c]Thursday, [d]Friday, $p < 0.001$.

Jump Testing

Relative Mean Power

Figure 2 displays relative mean power data. In Group A, no changes in mean power were observed between Monday and Wednesday ($p = 0.993$, $d = 0.03$) or Wednesday and Friday ($p = 0.134$, $d = 0.06$). While a significant increase in relative mean power was observed between Monday and Friday ($p = 0.021$, $d = 0.09$), the effect size indicates that any difference may be trivial. In addition, no significant differences between days were observed in Group B ($p = 0.079$, $d = 0.03 – 0.11$).

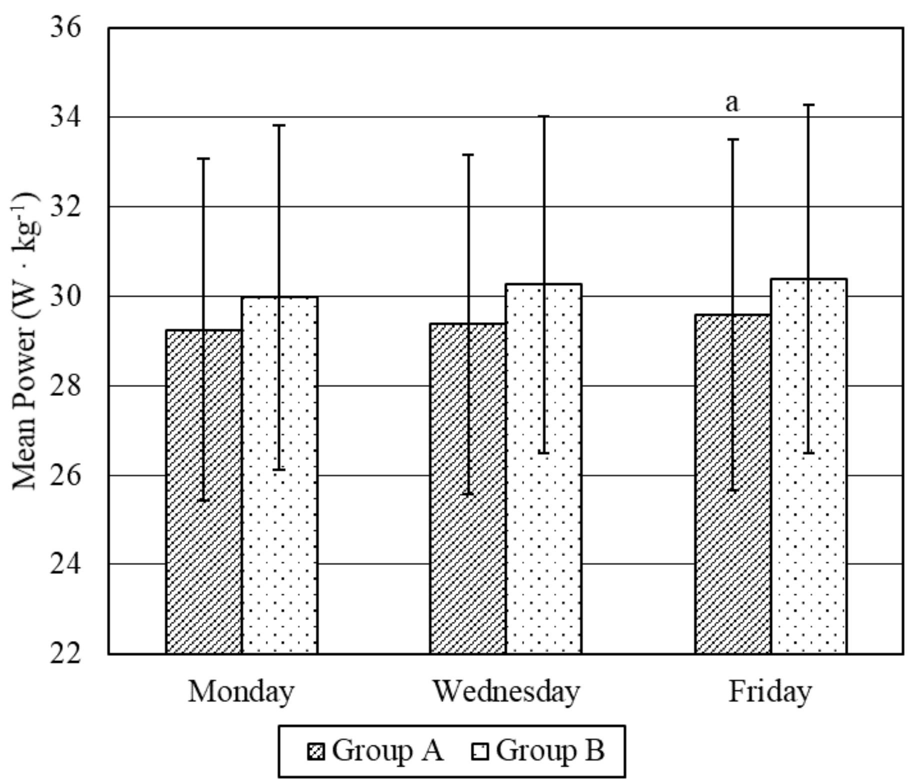

Figure 2. Mean power relative to bodyweight ($W \cdot kg^{-1}$, mean ± SD). Significantly different than [a]Monday, $p < 0.05$.

Peak Velocity

Peak velocity data is displayed in Figure 3. In Group A, peak velocity did not change from Monday to Wednesday ($p = 0.118$, $d = 0.06$), but did improve from Wednesday to Friday ($p = 0.007$, $d = 0.08$) and overall from Monday to Friday ($p < 0.001$, $d = 0.13$). However, improvements seen in peak velocity during the week may not be meaningful, as indicated by the trivial effect size. Group B had trivial increases from Monday to Wednesday ($p = 0.012$, $d = 0.12$), but no difference between Wednesday and Friday ($p = 1.000$, $d = 0.03$). Peak velocity did exhibit a significant increase from Monday to Friday ($p = 0.001$, $d = 0.12$), but similar to Group A, effect size suggests the change is minimal.

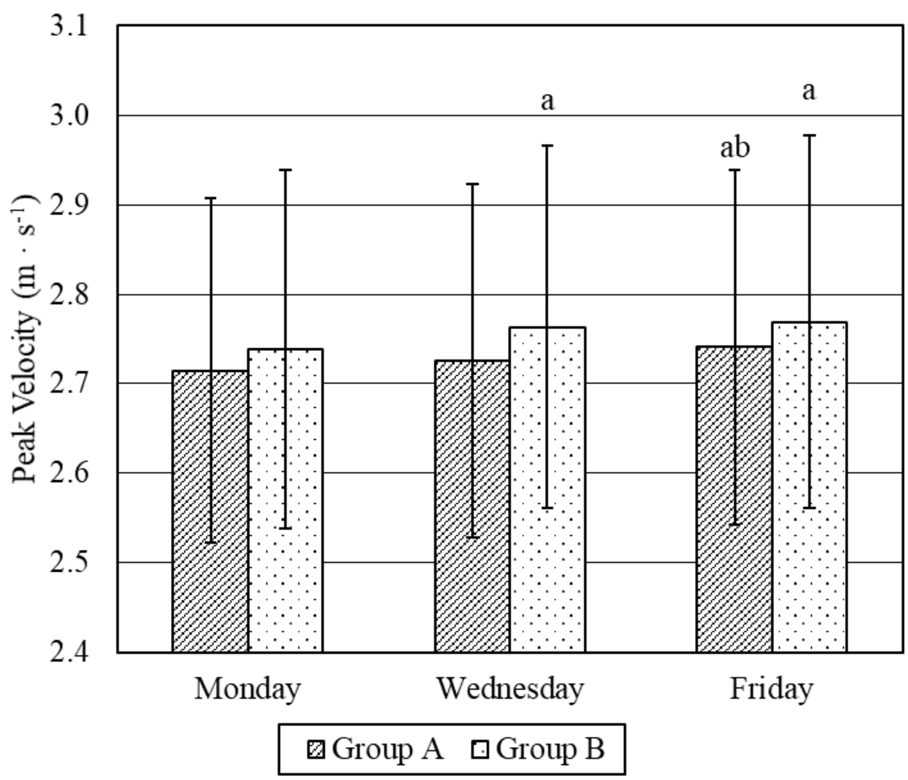

Figure 3. Peak velocity ($m \cdot s^{-1}$, mean ± SD). Significantly different than [a]Monday, [b]Wednesday, $p < 0.05$.

Jump Height

Figure 4 shows that jump height in Group A did not change from Monday to Wednesday ($p = 0.344$, $d = 0.04$) or from Wednesday to Friday ($p = 0.136$, $d = 0.05$); however, there was a trivial increase from Monday to Friday ($p = 0.006$, $d = 0.08$). Group B showed trivial improvement in jump height between Monday and Wednesday ($p = 0.044$, $d = 0.09$); however, no difference was found between Wednesday and Friday ($p = 1.000$, $d < 0.01$), or Monday and Friday ($p = 0.101$, $d = 0.08$).

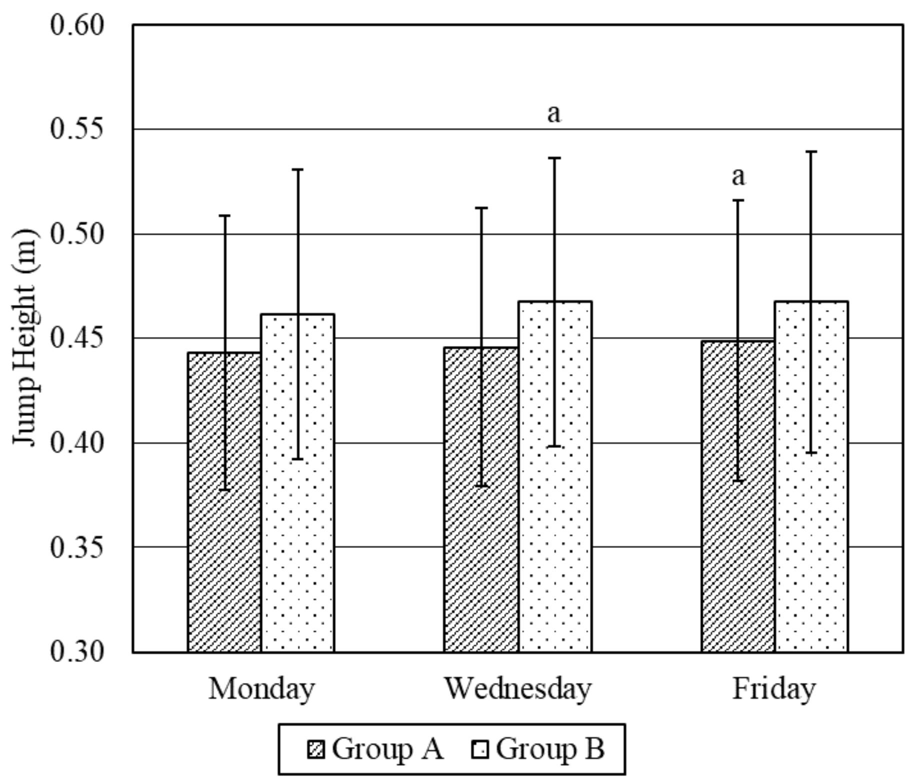

Figure 4. Jump height (m, mean ± SD). Significantly different than [a]Monday, $p < 0.05$.

Dip

Dip (Figure 5) during the CMJ increased significantly from Monday to Wednesday ($p = 0.015$, $d = 0.10$), Wednesday to Friday ($p = 0.001$, $d = 0.15$), and Monday to Friday ($p < 0.001$, $d = 0.25$) in Group A. Effect sizes indicate these differences are trivial and small. Likewise, Group B showed dip increased from Monday to Wednesday ($p = 0.018$, $d = 0.14$), but no change from Wednesday to Friday was observed ($p = 0.483$, $d = 0.07$). Across the entire week, there was a small increase in dip from Monday to Friday ($p = 0.014$, $d = 0.21$).

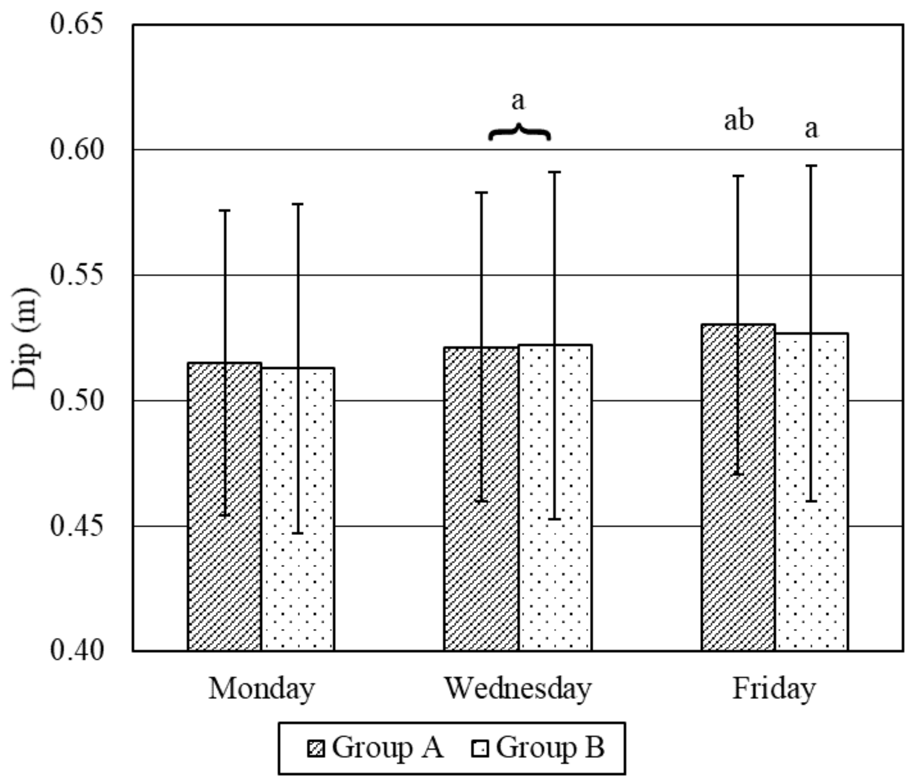

Figure 5. Dip (m, mean ± SD). Significantly different than [a]Monday, [b]Wednesday, $p < 0.05$.

Perceived Wellness Questionnaire

Fatigue

In Figure 6, fatigue in Group A was worse (lower score) on Wednesday than Monday ($p < 0.001$, $d = -0.57$) but improved (higher score) from Wednesday to Friday ($p = 0.004$, $d = 0.27$). Overall, fatigue was still worse (lower score) on Friday versus Monday ($p = 0.004$, $d = -0.31$). Group B fatigue scores also indicate players were more fatigued (lower score) on Wednesday than Monday ($p = 0.004$); however, this difference was only small ($d = -0.42$). While the improvement (higher score) from Wednesday to Friday was not significant ($p = 0.879$, $d = 0.14$), it was enough to return Friday's rating of fatigue similar to Monday ($p = 0.51$, $d = -0.29$).

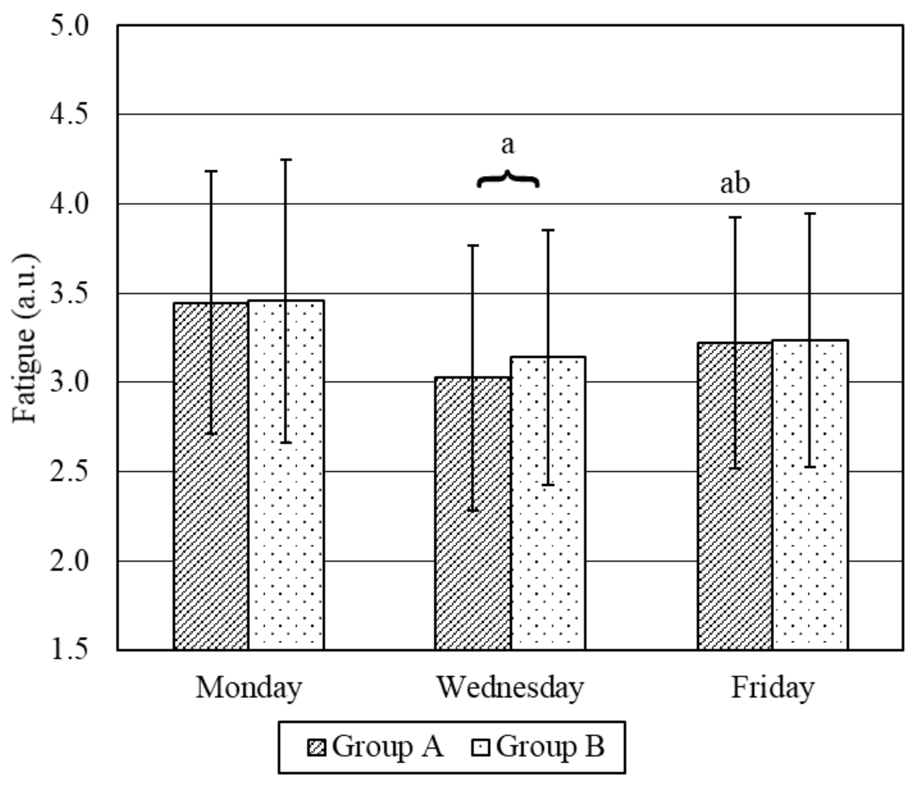

Figure 6. Fatigue (a.u., mean ± SD). Significantly different than [a]Monday, [b]Wednesday, $p < 0.05$.

General Muscle Soreness

Figure 7 displays general muscle soreness data. There was a large increase in muscle soreness (lower score) in Group A from Monday to Wednesday ($p < 0.001$, $d = -0.85$) and a moderate improvement (higher score) from Wednesday to Friday ($p < 0.001$, $d = 0.56$). Muscle soreness scores on Friday indicate the players were still more sore (lower score) than Monday ($p = 0.036$), but effect size ($d = -0.28$) indicates the difference was small. A large increase in muscle soreness was also observed in Group B on Wednesday compared to Monday ($p < 0.001$, $d = -0.90$). Further, muscle soreness improved (higher score) from Wednesday to Friday ($p < 0.001$, $d = 0.58$), resulting in a non-significant difference in muscle soreness between Monday and Friday ($p = 0.123$, $d = -0.33$).

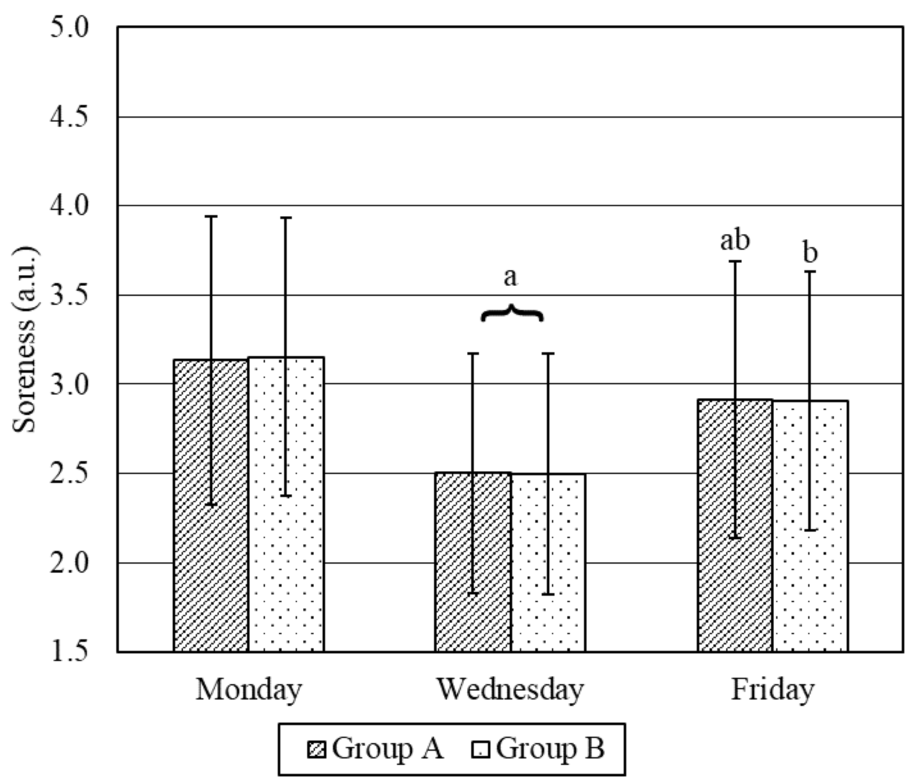

Figure 7. General muscle soreness (a.u., mean ± SD). Significantly different than [a]Monday, [b]Wednesday, $p < 0.05$.

Sleep Quality

No change in sleep quality was observed across days by either Group A (p = 0.684, d = -0.07 – 0.08) or Group B (p = 0.615, d = -0.42 – 0.14) (Figure 8).

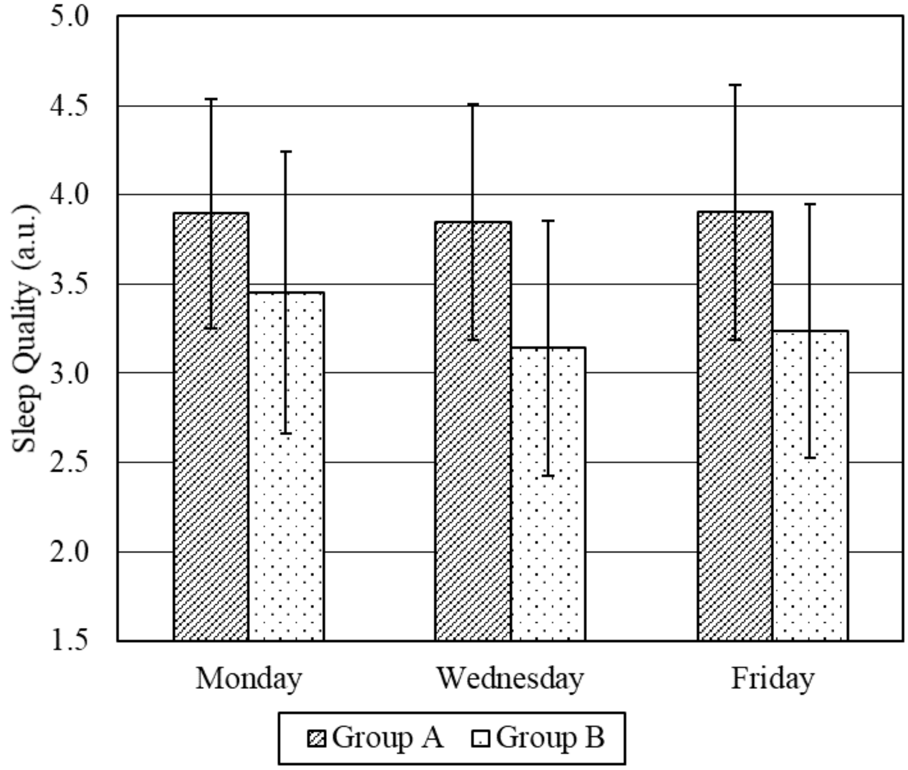

Figure 8. Sleep quality (a.u., mean ± SD).

Stress

Figure 9 shows that stress scores were the same between Monday and Wednesday (d = -0.19, p = 0.112) in Group A, but the improvement (higher score) between Wednesday and Friday was significant (p = 0.02), albeit small (d = 0.23). No difference in stress was observed between Monday and Friday (p = 1.000, d = 0.03). In Group B, stress scores were similar across all days (p = 0.198, d = -0.23 – 0.12).

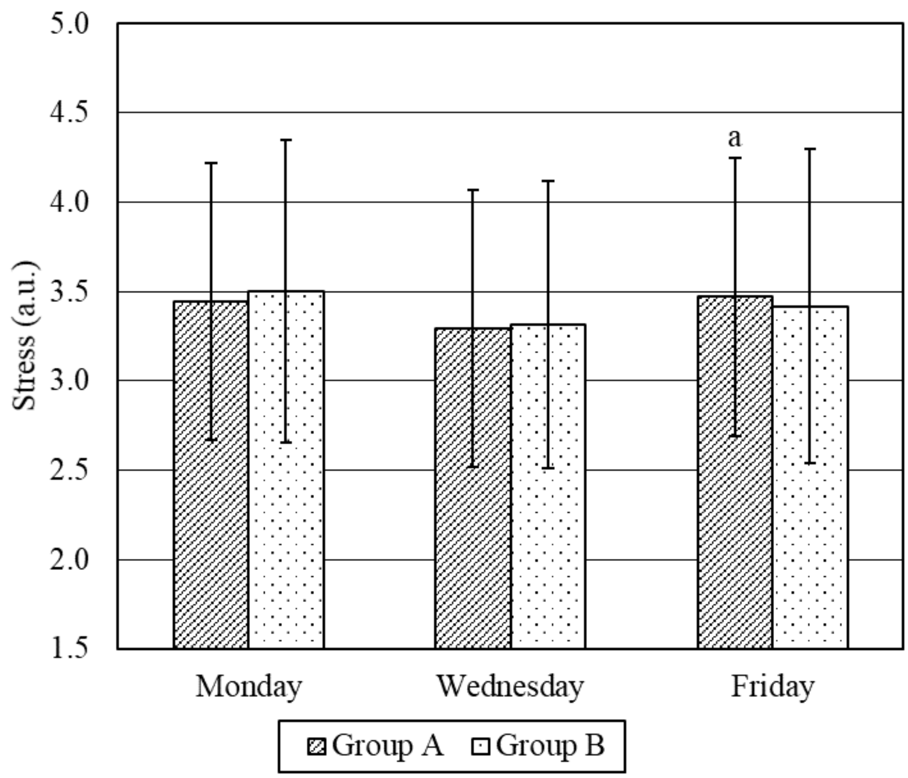

Figure 9. Stress (a.u., mean ± SD). Significantly different than [a]Wednesday, $p < 0.05$.

Mood

No significant differences in mood were identified between days for either Group A ($p = 0.247$, $d = -0.06 – 0.16$) or Group B ($p = 0.532$, $d = 0.02 – 0.13$) (Figure 10).

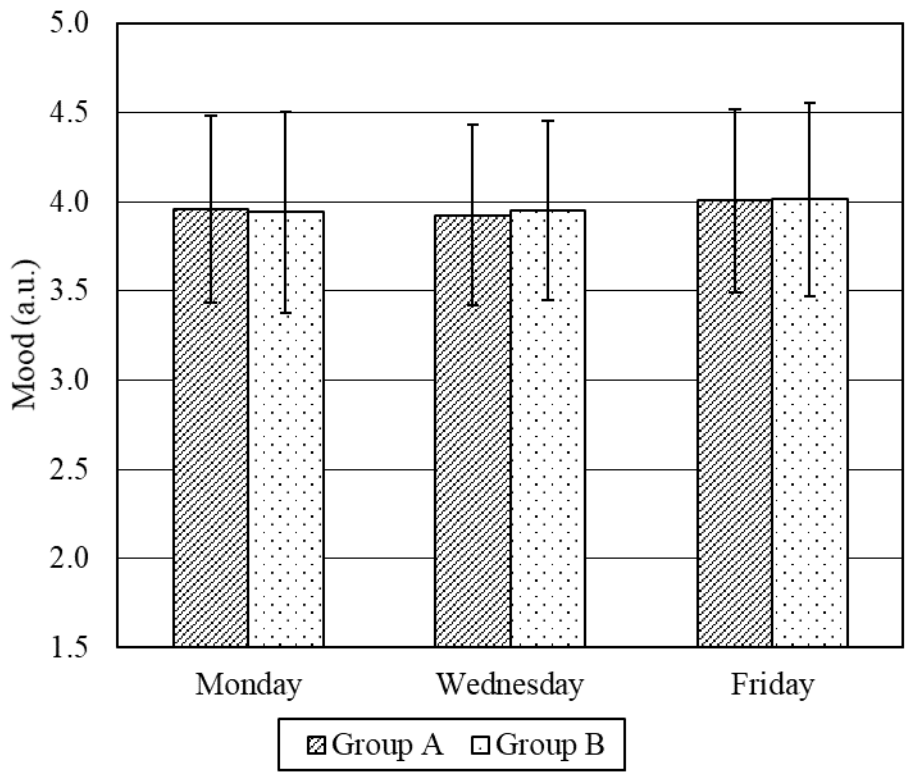

Figure 10. Mood (a.u., mean ± SD).

Overall Well-Being

Figure 11 displays overall well-being data. Group A showed a significant decrease (lower score) in overall well-being between Monday and Wednesday ($p < 0.001$, $d = -0.58$), but an improvement (higher score) in well-being between Wednesday and Friday ($p < 0.001$). Effect size indicates the improvement (higher score) between Wednesday and Friday was small ($d = 0.41$); however, the improvement was enough to increase (higher score) overall well-being on Friday to a level similar to Monday ($p = 0.359$, $d = -0.15$). Group B also had a significant decrease (lower score) in well-being between Monday and Wednesday ($p = 0.001$, $d = -0.53$) and a small improvement (higher score) ($p = 0.018$, $d = 0.29$) between Wednesday and Friday. Similar to Group A, well-being improved (higher score) enough between Wednesday and Friday to show no difference between Monday and Friday ($p = 0.276$, $d = -0.21$).

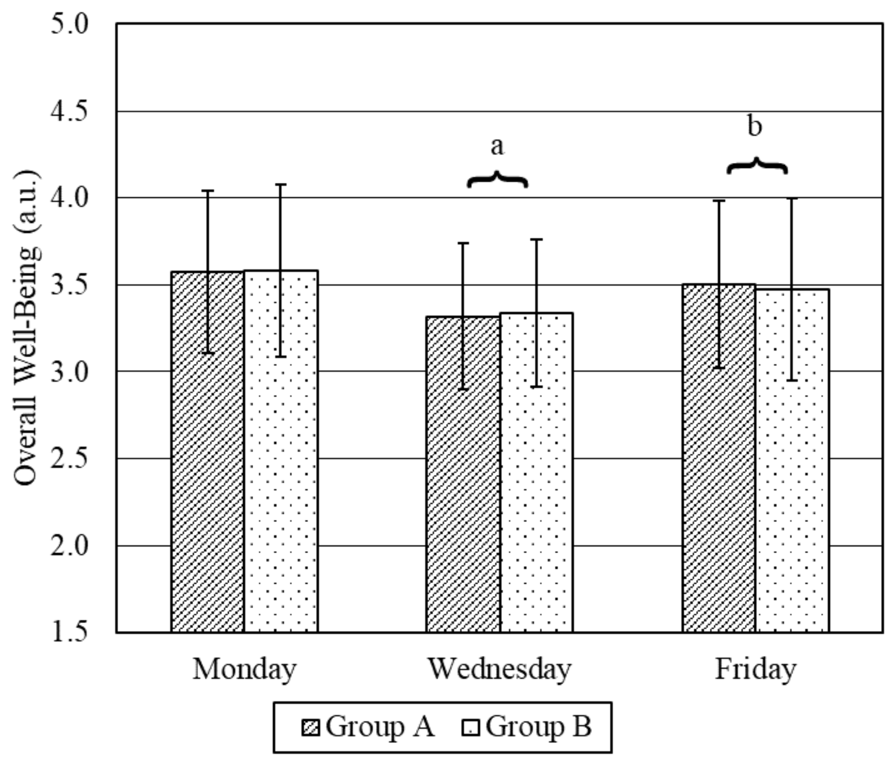

Figure 11. Overall well-being (a.u., mean ± SD). Significantly different than [a]Monday, [b]Wednesday, $p < 0.05$.

DISCUSSION

The purpose of this study was to determine if an undulating weekly practice periodization plan, with changes in ML on a daily basis, effectively managed NMF identified through CMJ performance and wellness scores between Monday and Friday within each week during the first six games (seven weeks) of an American college football season. We hypothesized that the fatigue accrued from increased training loads early in the week would disappear by the end of the practice week due to the changes in training load across the practice week. As noted previously, intragroup comparisons were made, but no analysis between groups was performed as this would violate the assumption of independence. Furthermore, although statistical significance was present at times within Group A and not in Group B, these differences may be directly related to the different number of observations between the two groups (n = 147 versus n = 78). Thus, effect size displays similar trends amongst the two groups. Loaded CMJ variables showed trivial or no changes from Monday to Friday. During the same time period, there was a small increase in dip. The change in dip suggests some NMF remained by the end of the week, but the effect size shows that the amount of fatigue was minimal. Perceptions of fatigue, general muscle soreness, and overall well-being became less favorable (more NMF) from Monday to Wednesday. The players' perceptions of these wellness variables became more favorable from Wednesday to Friday, with the Friday scores only slightly lower than Monday.

Recent studies observing training load in collegiate football have utilized a reverse linear periodization plan, with the highest training loads occurring on Tuesday and declining training loads on Wednesday, Thursday, and Friday until competition (Ward et al., 2018; Wellman et al., 2019a). In contrast, our study demonstrated an alternative periodization plan, using daily undulating MLs, with a low ML practice scheduled in the middle of the week in order to prevent an excessive accumulation of NMF from Monday to Friday.

Throughout the practice week, there were indications of trivial changes of performance in most CMJ variables, as relative mean power, peak velocity, and jump height improved slightly from Monday to Wednesday and further on Friday. Gathercole et al. (2015) noted similar trends during in-season team-sport collegiate athletes, as relative mean power, peak velocity, and jump height all had trivial or small improvements from 24 hours to 72 hours post-exercise ($d = 0.15 - 0.27$). Cormack et al. (2008) found relative mean power moderately increased from 24 hours through 72 hours post-match ($d = 0.47$) and further small improvement from 72 hours to 96 hours after the match ($d = 0.34$) in Australian Rules football. Jump height and peak velocity were similar from 42 hours to 90 hours post-match in Australian Rules football (Rowell et al., 2017). Overall, the above three studies showed that CMJ performance remains relatively stable across a practice week, which support our results for CMJ relative mean power, peak velocity, and jump height (Cormack et al., 2008; Gathercole et al., 2015; Rowell et al., 2017; Thomas et al., 2017).

Similar to mean power, peak velocity, and jump height, dip increased slightly across the week, with a small difference between Monday and Friday. The increase in dip indicates a change in CMJ strategy may exist during the eccentric phase. Skilled performers are thought to express a larger range of movement strategies to maintain performance output (Davids, Araújo, Vilar, Renshaw, & Pinder, 2013; Gathercole et al., 2015). A deeper dip when fatigued allows athletes more time and distance to produce force during the concentric phase to achieve the same CMJ output (Gathercole et al., 2015; Kennedy & Drake, 2017; Legg et al., 2017). An increase in duration of the eccentric phase is related to an increase in the dip of a CMJ, as more time is needed for the center of mass to descend lower. The increase in eccentric duration, coupled with jump height returning to baseline, suggests that a deeper dip may allow athletes more time to produce force so that they can maximize jump height in the presence of NMF (Gathercole et al., 2015; Kennedy & Drake, 2017). Kennedy and Drake (2017) found CMJ eccentric duration was greater 48 hours after an in-season training day when compared to a pre-training baseline, while peak velocity and jump height had returned to baseline values. Likewise, Gathercole et al. (2015) noted a small increase in the duration of the CMJ eccentric phase and decrease in the ratio of flight time to contraction time 24 hours and 72 hours after a fatiguing running exercise bout in team-sport athletes, while jump height had returned to baseline at each time point. Across an entire season, Legg et al. (2017) found a trivial to small dip increase during the time of the season when training loads were larger. It is important to note that since the change in dip in our study was small from Monday to Friday, there is evidence that training load had a minimal effect on NMF over the course of the practice week. In contrast to our results, some studies demonstrate that dip is smaller in the presence of fatigue (Rodacki, Fowler, & Bennett, 2001; Schmitz et al., 2014), but it is important to note that these studies monitored changes across one training session instead of prolonged changes across multiple days.

Throughout the practice week, we observed moderate or large increases (worse scores) in perceptions of fatigue, soreness, and overall well-being from Monday to Wednesday. This was likely due to high cumulative MLs on Monday and Tuesday, along with the strength training session on Tuesday. Fullagar, Govus, Hanisch, and Murray (2017) also found that collegiate football players report fatigue and muscle soreness are greatest on Tuesday and Wednesday of the practice week. Unfortunately, Fullagar et al. (2017) did not report training loads of practices to attempt to explain their findings. In our study, from Wednesday to Friday, there were small improvements in these wellness variables, indicating that the practice MLs on Wednesday and Thursday, as well as the loads accumulated from the strength training session on Thursday, were low enough to allow these variables to improve. While not measured, further progression in these wellness variables from Friday to Saturday was expected, due to Friday's ML being the lowest of the week.

Unlike the other wellness variables, sleep quality, stress, and mood did not significantly change across the weekly microcycle. The lack of daily changes for each of these three variables may indicate they are not affected by the degree of changes in training loads used in this study. Other studies support our results, reporting little to no differences in sleep quality, stress, and mood in response to training (Johnston et al., 2013; McLean et al., 2010; McLean et al., 2012).

There are a few key limitations in our study. For one, we did not have a traditional reverse linear periodization practice schedule to compare CMJ and wellness responses to other results. As a result, we cannot conclude this periodization scheme is better than the traditional practice week; however, anecdotal responses of our subjects indicate they like the mid-week recovery day after the heavy training load from Tuesday strength training and practice compared to other periodization schemes. Mechanical load was not monitored during games, as we did not want the athletes to worry about the straps falling off during competition. Without game data, we cannot account for those training loads and their impact on jump performance and wellness scores on Monday.

Overall, the findings of our study demonstrate that our daily undulating periodization practice plan effectively managed NMF from Monday to Friday. Trivial increases in CMJ variables indicated CMJ performance was maintained throughout the practice week despite fluctuations in wellness variables, indicating that the periodization plan was successful in managing NMF. The small increase in dip in the loaded CMJ may suggest that a change in movement strategy was used to maintain CMJ performance from Monday to Friday. Regarding wellness variables, the increases in perceptions of fatigue, soreness, and decrease in overall well-being from Monday to Wednesday indicate the players may have accumulated NMF from the training loads of strength training and practice on Monday and Tuesday. However, improvements in these variables from Wednesday to Friday suggest a reduction in NMF likely occurred, due to training loads being appropriately managed in Wednesday through Friday practices and a lesser demanding strength training session. In addition, since Friday's ML was the lowest of the week, perceptions of fatigue, muscle soreness, and overall well-being were expected to improve between Friday morning's wellness scores and Saturday's game time. Since CMJ variables remained similar while perceptual fatigue, soreness, and overall well-being fluctuated, we suggest that NMF was effectively managed from Monday to Friday. Some wellness variables, such as sleep quality, stress, and mood, did not reflect changes in training loads, and consequently, changes in NMF.

Practical Applications

This study indicates an undulating periodization of training loads across a practice week of collegiate football successfully manages NMF. Loaded CMJ performance may be maintained in the presence of NMF due to a change in jump strategy during the eccentric phase of the movement. Wellness questionnaires are an inexpensive, easily administered tool that may also be used regularly to assess an athlete's readiness to train/compete. In addition, reporting responses from wellness questions to sport coaches multiple times per week enables coaches to make acute individual adjustments to each player's subsequent training loads, aiding in successful management of fatigue between competitions.

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APPENDIX A

INFORMED CONSENT FORM

Informed Consent

Protocol Title: Impact of Neuromuscular & Perceptual Fatigue from Practice Training Loads on Weekly Readiness to Play during an NCAA Division III Collegiate Football Season

Principal Investigator: John Schimenz
UW-La Crosse
222 Mitchell Hall
La Crosse, WI 54601
414-460-3418

1. I, ___________________________________, give my informed consent to participate in this study, whose purpose is to examine changes in neuromuscular and perceptual fatigue across practice microcycles during an NCAA Division III collegiate football season, using a weekly periodization plan that is different from what is traditionally done in collegiate football. I have been informed that this study is under the direction of Glenn Wright, Ph.D., faculty in the Exercise & Sport Science department. I consent to the presentation, publication and other release of summary data from the study that is not individually identifiable.
2. I have been informed that my participation in this study will require me to:
    a. Wear a chest strap during all scheduled practice times.
    b. Participate in a jump assessment three times per week in 225 Mitchell Hall that consists of a brief warm up and a total of six maximal vertical jumps at each session with a 20 kg barbell across my shoulders.
3. I have been informed that I will complete a health/wellness questionnaire consisting of five questions at each jump testing session.
4. I have been informed that all data will remain confidential through a password protected laptop computer that only the research team will have access to, and that any published data will not reveal my identity.
5. I have been informed that there are no foreseeable risks associated with the study other than possible discomfort due to the chest strap and minimal risk of fatigue or injury from the jump testing. Individuals trained in CPR, First Aid, and use of an AED will be in the laboratory, and the testing will be terminated if complications occur.
6. I have been informed that through this study, I may be able to see changes in my jumping performance and may increase self-awareness of when I need more rest due to fatigue. As a result of data produced during the study, the football coaching staff may be able to better understand fatigue associated with practice schedule.
7. I have been informed that the investigator will answer any questions regarding the procedures throughout the course of the study.

8. I have been informed that I am free to decline to participate or to withdraw from the study at any time without penalty or prejudice.
9. Concerns about any aspects of this study may be referred to John Schimenz at 414-460-3418 or Dr. Glenn Wright at 608-785-8689. Questions about the protection of human subjects may be addressed to the Chair of the UW-L Institutional Review Board 608-758-6892 or irb@uwlax.edu.

Participant Signature: ______________________________________ Date: __________

Investigator Signature: ______________________________________ Date: __________

APPENDIX B

WELLNESS QUESTIONNAIRE

SCORE (INCRE-MENTS OF 0.5)	5	4	3	2	1
FATIGUE	Very fresh	Fresh	Normal	More tired than normal	Always tired
SLEEP QUALITY	Very restful	Good	Difficulty falling asleep	Restless sleep	Insomnia
GENERAL MUSCLE SORENESS	Feeling great	Feeling good	Normal	Increase in soreness/tigh tness	Very sore
STRESS LEVELS	Very relaxed	Relaxed	Normal	Feeling stressed	Highly stressed
MOOD	Very positive mood	A generally good mood	Less interested in others &/or activities than usual	Snappiness at teammates, family, and co-workers	Highly annoyed / irritated / down

APPENDIX C

REVIEW OF LITERATURE

INTRODUCTION

American football is a physical team sport that incorporates brief, intermittent instances of high-intensity activity (Iosia & Bishop, 2008; Rhea, Hunter, & Hunter, 2006; Wellman, Coad, Goulet, & McLellan, 2017b). During the in-season period, in order to prepare for weekly games, teams perform drills and exercises at training sessions to maximize their athletes' performances on the days of competition. The amount of work performed during these sessions, or training load, must be tracked, as chronic, excessive work may lead to a decrease in force or power production, which can be termed neuromuscular fatigue (NMF) (Boyas & Guével, 2011; Meeusen et al., 2013). To detect NMF, a variety of physical performance test variables and subjective measures of wellness have been used (McLean, Coutts, Kelly, McGuigan, & Cormack, 2010; Twist & Highton, 2013). The data collected from these performance tests and subjective measures may be used to educate coaches and sports scientists alike so that adjustments to the periodization plan can be made in order to peak athletes for competitions. Therefore, the purpose of this review is to determine the mechanisms of NMF, explore methods to monitor exercise training loads and NMF, and analyze the sport-specific demands of American football.

NEUROMUSCULAR FATIGUE

In order to perform athletic actions, skeletal muscle contraction must occur to produce force. The whole muscle contraction process begins in the brain, where an action potential (AP) from the motor cortex propagates down the efferent tracts in the spinal cord to stimulate alpha motoneurons and further propagates an AP to the neuromuscular junction (NMJ) between the terminal axon and motor end-plate of a muscle fiber. At the NMJ, acetylcholine is released causing a Na^+ influx depolarizing the motor end plate of the muscle fiber. The AP travels down the sarcolemma into the transverse tubules (t-tubules), signaling the release of calcium (Ca^{2+}) from the sarcoplasmic reticulum (SR) by activating voltage-gated Ca^{2+} channels. Calcium binds to troponin on the thin filament, exposing crossbridge (CB) binding sites on actin. The myosin heads attach to the actin at the CB binding sites, and the splitting of adenosine triphosphate (ATP) into adenosine diphosphate (ADP) and inorganic phosphate (P_i) on the CBs provides energy for the CB power stroke. Shortening of the muscle fibers ensues, which leads to force production (MacDougall & Sale, 2014).

Neuromuscular fatigue is any exercise-induced attenuation in force or power production in the muscle (Boyas & Guével, 2011). In the context of exercise, there are a number of possible mechanisms that occur anywhere from the brain to the muscle which may lead to NMF. Neural mechanisms of fatigue, which occur at or prior to the NMJ, include central drive from the brain and spinal cord to recruit motor units, propagation of the AP to the terminal end of the motoneuron, and the release of acetylcholine at the NMJ (Enoka, 2002). Muscular mechanisms of fatigue, which occur anywhere after the NMJ, include sarcolemmal propagation, excitation-contraction coupling, availability of metabolic substrates, CB cycling, and muscle blood flow (Enoka, 2002). Regardless of whether the fatigue mechanisms are neural or muscular, NMF ultimately causes a disruption of CB cycling related to a decline in force and power (MacDougall & Sale, 2014). Both neural and muscular mechanisms of fatigue will be discussed in the next two sections.

Neural Mechanisms of NMF

Overall, neural mechanisms of fatigue result in a reduction in activation of motor units. A failure of activating adequate motor units consists of not maintaining recruitment of motor units and/or firing rate frequency necessary to maintain force production. Verbal encouragement (Enoka, 2002) and presence of competitors (Wilmore, 1968) helps improve performance implicates a lack of motivation as a key culprit, which may cause a submaximal voluntary stimulus from the motor cortex consequently leading to an incomplete activation of motor units and attenuation in force production (MacDougall & Sale, 2014).

Changes in afferent feedback from exercise may inhibit force production by decreasing motor drive from the central nervous system (CNS) (Pitcher & Miles, 2002). For example, an increased perception of pain has been shown to decrease force output (Le Pera et al., 2001). Besides injury, muscle pain is produced by the activation of nociceptors that send afferent signals to the brain, which may lead to a decline in motor unit recruitment. Metabolites, such as ATP present in the extracellular fluid following muscle damage and hydrogen ions (H^+) that are elevated during high intensity muscle contraction, activate nerve endings of these muscle nociceptors (Mense, 2008). In addition, Type III and IV nerve fibers, which help regulate cardiovascular and ventilatory responses to exercise, may send inhibitory afferent signals back to the CNS during high intensity exercise, decreasing central motor drive (Amann, 2012). Excitatory input from the muscle spindle is attenuated with the accumulation of NMF (Macefield, Hagbarth, Gorman, Gandevia, & Burke, 1991; Gandevia, 2001). The net effect of the above afferent mechanisms leads to less central motor drive, decreasing motor unit activation and force production (Goodall, Charlton, Howatson, & Thomas, 2015).

Muscle Mechanisms of NMF

Excitation-contraction (EC) coupling is the process by which the muscle AP triggers the release of Ca^{2+} from the SR, initiating shortening of the muscle fiber (MacDougall & Sale, 2014). Increases in extracellular potassium (K^+) from repeated rapid stimuli to the muscle fibers may accumulate outside the sarcolemma and especially in the t-tubules. The build-up of extracellular K^+ in the t-tubules likely hinders the propagation of the AP into the t-tubules affecting the EC coupling by limiting the release of Ca^{2+} from the SR, ultimately limiting the number of available CB binding sites on the thin filament (Westerblad, Lee, Lamb, Bolsover, & Allen, 1990). The attenuation in force from a rise in extracellular K^+ is typically evident during high frequency muscle stimulation during high intensity muscular contractions and is referred to as high frequency fatigue (HFF) (Jones, 1996). Recovery from HFF is relatively short, possibly lasting up to 30 minutes depending on the severity and duration of exercise (Allen, Lamb, & Westerblad, 2002; Jones, Bigland-Ritchie, & Edwards, 1979).

Fatigue may also be apparent when a muscle is stimulated at low frequencies. Referred to as low frequency fatigue (LFF), the mechanism that causes LFF is not entirely understood and may be multifactorial. First identified by Edwards, Hill, Jones, and Merton (1977), LFF is characterized by a decrement in force production due to a reduction in the release of Ca^{2+} from the SR (Jones, 1996). Low frequency fatigue is mainly exhibited during low intensity muscular contractions, although it affects force production at all intensities. Another characteristic of LFF is that it exists without any electrical or metabolic disturbances in the muscle. It should also be noted that LFF could be present because of high volumes of either low or high intensity exercise (Jones, 1996). It may take hours or days to fully recover from LFF (Edwards et al., 1977; Jones, 1996; Smith, Martin, Gandevia, & Taylor, 2007).

Muscle damage, typically caused by eccentric exercise and collisions during sport play, has been suggested to be a contributor to NMF (Jones, Newham, & Torgan, 1989) and may be a factor related to LFF. One possible mechanism explaining changes in force production due to eccentric muscle damage is the change in the sarcomere's length-dependent relationship (Jones et al., 1989). When muscle fibers are damaged during eccentric contraction or isometric contraction when the muscle is stretched, it is thought that the middle sarcomeres of a fiber become damaged to the point where these sarcomeres become overextended (Jones et al., 1989; Morgan 1990). Concurrently, the functional sarcomeres near the ends of the muscle fibers are significantly shortened compared to the non-damaged state (Jones et al., 1989; Morgan 1990). According to the length-force relationship, both overextended and shortened lengths of a sarcomere lead to decreases in force production (Rassier, Macintosh, & Herzog, 1999). Furthermore, muscle damage has also been suggested to cause rupture to the t-tubules (Takekura, Fujinami, Nishizawa, Ogasawara, & Kasuga, 2001) leading to less Ca^{2+} release from the SR and a corresponding attenuation in force production (Balnave & Allen, 1995). Muscle damage typically peaks 1-3 days post-exercise, but it may last as long as 6-8 days depending on its severity (Fridén, Sjöström, & Ekblom, 1983; Peake, Neubauer, Della Gatta, & Nosaka, 2017). Since it also may take days for LFF to dissipate (Edwards et al., 1977; Jones, 1996; Smith et al., 2007), it is difficult to determine if muscle damage is related to LFF or is present during other events that take place in the same period.

Neuromuscular fatigue may also originate as metabolic fatigue related to depletion of energy stores or accumulation of metabolites in the muscle. During high intensity exercise such as sprinting, there is a rapid depletion of high-energy phosphate stores, such as ATP and phosphocreatine (PCr), especially in Type II fibers (Sargeant & De Haan, 2006). ATP is split to provide energy for CB cycling and PCr provides the most rapid pathway for resynthesizing ATP (MacDougall & Sale, 2014). Complete restoration of the phosphagen stores following a single short sprint may take 2 - 5 minutes or may be longer in a repeated bout of short sprints where PCr depletion may be greater (Dawson et al., 1997). Restoring PCr to near original levels is strongly related to the restoration of force and power during high intensity exercise (Bogdanis, Nevill, Boobis, Lakomy, & Nevill, 1995; Mendez-Villanueva, Edge, Suriano, Hamer, & Bishop, 2012). Bogdanis et al. (1995) discovered after performing two repeated 30-second maximal sprints on a stationary bike, the extent of PCr resynthesis from the first sprint had strong positive correlations with peak power output, maximum speed, and maximum power during the first 6 seconds of the second sprint ($r = 0.71 - 0.86$, $p < 0.05$). Similarly, Mendez-

Villanueva et al. (2012) had subjects perform two sets of 6-second sprints. The first set consisted of ten sprints and the second set of five sprints followed 6 minutes of recovery. During both sets, there was 30 seconds recovery between sprints. Strong positive correlations ($r = 0.79$, $p < 0.05$) were observed between PCr resynthesis and the total work done in the first sprint of the second set. In addition, there was a strong positive correlation ($r = 0.67$, $p < 0.05$) between PCr resynthesis and the sum of the total work done in the second set of 6-second sprints.

Muscle glycogen is depleted during repeated, high-intensity exercise, especially in the Type II fibers (Balsom, Gaitanos, Söderlund, & Ekblom, 1999; Gollnick, Armstrong, Sembrowich, Shepherd, & Saltin, 1973). Low muscle glycogen levels impair high-intensity exercise performance. Saltin (1973) reported soccer players whose muscle glycogen stores were only partially restored prior to the match covered significantly less distance at slower speeds compared to their teammates whose muscle glycogen stores were fully restored prior to the match. Similarly, Krustrup et al. (2006) detected soccer players' muscle glycogen levels declining by 42% across a soccer match, which corroborated with significantly slower 30-m sprint times. During prolonged exercise, low glycogen levels minimize the effectiveness of glycogenolysis for restoring muscle stores of ATP (Mul, Stanford, Hirshman, & Goodyear, 2015). As a result, a greater reliance on the declining PCr stores and aerobic metabolism is required, which leads to decreased performance (Balsom et al., 1999; Vøllestad, Vaage, & Hermansen, 1984). Therefore, muscle glycogen stores need to be maintained for team sport athletes to avoid muscle fatigue. To replenish muscle glycogen stores quickly, post-exercise consumption of carbohydrates is needed (Cogan et al., 2018; Pascoe, Costill, Fink, Robergs, & Zachwieja, 1993).

In addition to depletion of energy sources, an accumulation of metabolites may affect the ability to produce muscular fatigue, such as the accumulation of P_i, H^+, and ADP, which all lead to a reduction in ATP synthesis through metabolic pathways. A rise in the concentration of P_i from the rapid breakdown of ATP and PCr negatively affects the release of Ca^{2+} from the SR. Accumulating P_i may bind to Ca^{2+} in the SR, minimizing the amount of Ca^{2+} available for release, limiting the number of available CB binding sites (Allen, Kabbara, & Westerblad, 2002). The fatiguing effects of P_i accumulation may be short-lived as a return of P_i to pre-exercise levels may take only 2-5 minutes (Baker, Kostov, Miller, & Weiner, 1993).

An accumulation of H^+ may have several negative effects. Decreases in pH (i.e. increased [H+]) in the muscle have been shown to slow down the production of ATP through glycogenolysis and glycolysis by inhibiting their respective rate-limiting enzymes, phosphorylase and phosphofructokinase (Hollidge-Horvat, Parolin, Wong, Jones, & Heigenhauser, 1999). In addition, some evidence has shown that increased $[H^+]$ may diminish the sensitivity of myofibrillar proteins to Ca^{2+}, which reduces the number and strength of each CB attachment, decreasing force production (Allen et al., 2008; Cairns, 2006; Fitts, 2008). However, there is also evidence that accumulation of H^+ may have little effect on attenuated force production when normal physiological temperatures are maintained (Mendez-Villanueva et al., 2012; Westerblad, Bruton, & Lannergren, 1997). Recovery of blood pH following high intensity exercise has been shown to take between 60-75 minutes to return to baseline, depending on whether recovery was active (40% VO2 max) or passive, respectively (Fairchild et al. 2003).

During sustained high-intensity exercise or exercise of long duration, ADP accumulation may contribute to NMF (McLester, 1997). With high concentrations of ADP, the rate of CB cycling slows due to the inhibition of myosin ATPase, which is the enzyme used to metabolize ATP (De La Cruz, Sweeney, & Ostap, 2000; Abbott & Mannherz, 1970). To temporarily reduce the ADP concentration during sustained high intensity exercise, the enzyme myokinase uses two ADP molecules to create ATP and AMP (Sahlin & Broberg, 1990). Through a one-way chemical reaction, the enzyme adenylate kinase deaminates ADP to inosine monophosphate (IMP) and ammonia to minimize the accumulation of ADP (Sahlin & Broberg, 1990), therefore lowering total adenine nucleotide concentration, specifically ATP, for an extended time (Stathis, Febbraio, Carey, & Snow, 1994).

In summary, NMF is a decrease in force and power production due to exercise. There are a number of locations, from the brain through the CB where mechanisms of fatigue may occur. These mechanisms can be classified as neural or muscular. Knowledge of the mechanisms of fatigue, especially the specific time frames for recovery, may allow athletes and coaches to plan training programs and practice schedules around important events associated with competition. Methods of detecting NMF, so that acute adjustments in the training program can be made, are necessary to peak performance. Such methods will be analyzed in the next three sections.

Monitoring NMF

Direct measurement of NMF in sport athletes is a difficult process. It would seem sensible to measure the extent of fatigue directly by a maximal test of performance in the athlete's competitive event; however, this becomes problematic for team sport athletes since each position on a team depends on others to perform successfully. In addition, maximal sport specific performance efforts in some sports may add further fatigue as a result of monitoring if performed during the competitive season (Bishop, Jones, & Woods, 2008; Taylor, Chapman, Cronin, Newton, & Gill, 2012). As a result, performance tests and subjective measures of well-being have alternatively been used to monitor an athlete's level of fatigue in-season (McLean et al., 2010; Twist & Highton, 2013). For example, McLean et al. (2010) noted that countermovement vertical jump (CMJ) performance testing and subjective questionnaires are useful for in-season monitoring for changes in fatigue status that appears to be related to training loads in team sports. In order to be valid, the performance tests should mimic actions that athletes perform in practices and competitions (Gathercole, Sporer, Stellingwerff, & Sleivert, 2015c; McMaster, Gill, Cronin, & McGuigan, 2014; Twist & Highton, 2013).

Vertical Jump Test

While there are many different performance tests available, the vertical jump has been used frequently to monitor NMF in individual and team sport athletes (Claudino et al., 2017; Gathercole, Sporer, Stellingwerff, & Sleivert, 2015b; McLellan & Lovell, 2012). Jump tests are popular due to their practicality, as they are simple to administer, time-efficient, cause little fatigue, and are reliable (Balloch, 2018; Gathercole et al., 2015b; Gathercole et al., 2015c; Taylor, Cronin, Gill, Chapman, & Sheppard, 2010;

Twist & Highton, 2013). The CMJ is frequently used because many sport actions utilize the stretch-shortening cycle (SSC) through sprints and jumps. In addition, the CMJ is more sensitive to NMF compared to a static jump, and performance of the CMJ is more repeatable compared to a drop jump (Gathercole et al., 2015c). While adding additional mass (e.g. holding a barbell on the shoulders), or “loading”, does show significant changes in CMJ variables (Cormie, McBride, & McCaulley, 2008), it is still a reliable test (Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008).

A number of variables can be tracked during a CMJ (time, jump height, power, force, velocity, rate of force production, duration, etc.) at various phases of the movement (eccentric, concentric, flight, or a combination of phases) to detect NMF (Claudino et al., 2017, Gathercole et al., 2015b). Gathercole et al. (2015b) monitored collegiate team sport athletes before and after a single fatigue-inducing exercise session. The authors noted CMJ mean power, peak velocity, flight time, and jump height were all depressed from baseline scores immediately following exercise. Similar decrements in CMJ performance have been detected after team-sport competitions when looking at relative mean power (Cormack, Newton, & McGuigan, 2008a), flight time (Cormack et al., 2008a; McLean et al., 2010), ratio of flight time to contraction time (FT:CT) (Cormack et al., 2008a), peak power (McLellan & Lovell, 2012), peak rate of force development (McLellan & Lovell, 2012), and peak velocity (Hills & Rogerson, 2018). Thus, there are a number of different variables of the CMJ have been used successfully to identify NMF.

Unfortunately, it is debatable as to what jumping variables are most sensitive to NMF (Taylor et al., 2012), since many studies have shown differences in the way some variables respond to training and competition loads. McLean et al. (2010) monitored

CMJ performance at different time-points during rugby inter-match microcycles. They observed rugby players having significantly shorter CMJ flight times one day post-match compared to one day before the match. However, relative power showed no significant changes in the same period. In another study, CMJ variables were assessed for the suitability as markers of fatigue over a six-week training block with progressive increase in training loads (Gathercole, Sporer, and Stellingwerff, 2015a). Flight time, peak displacement, force at zero velocity, and time to peak force showed changes from baseline that were indicative of diminished neuromuscular function. At the same time, typical variables of CMJ testing, i.e., jump height, mean power, and peak velocity, were not different from baseline during the same period (Gathercole et al., 2015a). In contrast to the above studies, Roe et al. (2017) noted that CMJ performance indicated by mean and peak power showed greater decreases at different times of a 6-week training block in rugby players than flight time during the same testing sessions. Additionally, others have observed that, while peak power and peak rate of force development in a CMJ were both significantly depressed 24 hours following a rugby match, peak force returned to pre-match scores (McLellan and Lovell, 2012). Therefore, the above studies indicate it is unclear which CMJ variables are more sensitive to NMF.

Variables that incorporate changes in movement strategy of the CMJ, especially during the eccentric phase, may be important to consider in addition to concentric-only variables (Gathercole et al., 2015b; Gathercole, Stellingwerff, & Sporer, 2015d, Kennedy & Drake, 2017; Legg, Pyne, Semple, & Ball, 2017). This change in movement strategy is evident when looking at the center of mass displacement, or “dip”, during the loading phase of the CMJ. When analyzing fatigue across a training session, dip tends to be less when fatigue is greater, primarily due to reduced knee angular displacement (Dello Iacono et al., 2017; Rodacki, Fowler, & Bennett, 2001; Schmitz, Cone, Copple, Henson, & Shultz, 2014; Thorlund, Michalsik, Madsen, & Aagaard, 2008). Rodacki et al. (2001) noted fatigued athletes activated their muscles sooner during the eccentric phase of a CMJ than when they were not fatigued. The authors proposed the earlier activation of the leg extensor muscles and resulting smaller dip during the eccentric phase is a strategy that allows the knee joints to decelerate more gradually than in a non-fatigued condition. This strategy may be performed to avoid producing muscle damage and maintain jump performance when fatigued by taking advantage of knee stiffness in a more extended position (Rodacki et al., 2001; Schmitz et al., 2014). For example, Schmitz et al. (2014) monitored CMJ height and other jump variables before, during, and after a 90-minute intermittent exercise protocol that mimicked the biomechanical and physiological demands of intermittent field or court sports. Over the course of the training session, jump height was maintained, but the dip was smaller. Despite the shorter dip, Rodacki et al. (2001) also detected longer durations of the eccentric and concentric phases in a fatigued-state, which supports the notion that a longer total contraction time (CT) may be a change in jump strategy in the presence of NMF. In fact, FT:CT has been shown to be a good indicator of fatigue from exercise in team-sport athletes (Cormack et al., 2008a; Cormack, Newton, McGuigan, & Cormie, 2008b; Gathercole et al., 2015b). However, when looking at dip across an entire season, Legg, Pyne, Semple, and Ball (2017) observed an increase dip occurred during the part of a basketball season with the highest training loads, while jump height stayed the same. Legg et al. (2017) suggested the players increased their dip in order to create more power to reach the same jump height.

While dip was not measured directly, Kennedy and Drake (2017) found that rugby players had longer eccentric phases for their CMJs at 48 hours after an in-season training day, while jump height had returned to baseline, which gives evidence that dip was greater.

The contrasting evidence showing a higher or lower dip in the presence of fatigue is more conflicting when looking at CMJ movement strategy changes with positive adaptations from training (Cormie, McBride, & McCaulley, 2009; Cormie, McGuigan, & Newton, 2010; Gathercole et al., 2015d). For example, Cormie, et al. (2009) observed untrained subjects before and after completion of a 12-week ballistic training program. As expected, CMJ peak power, peak velocity, and concentric rate of force development (RFD) all significantly improved from pre- to post-testing. However, peak eccentric force, peak eccentric RFD, peak displacement, and the area under the force-velocity curve also significantly improved. More specifically, when looking at the displacement-time curve graph, the increase in dip was greater than the increase in height off the ground. This increase in dip corresponded with a greater change in the eccentric phase compared to the concentric phase of the jump in the area under the force-velocity curve. Evidence suggests that CMJs produce relatively higher levels of force during the initial portion of the concentric phase than static jumps, and this additional amount of force contributes to greater concentric RFD (Walshe, Wilson, & Ettema, 1998). Therefore, Cormie et al. (2009) proposed that a greater dip following positive training adaptation allowed for greater peak eccentric force and peak eccentric RFD and that eccentric variables have large contributions to the improvements in the concentric phase of the CMJ. Similarly, Cormie et al. (2010) noted that many CMJ eccentric (e.g. eccentric

RFD, peak eccentric force) and concentric (e.g. average concentric power, peak concentric velocity) variables significantly improved over a 10-week ballistic training program. However, static jump concentric variables did not significantly improve, which supports the authors' notion that the changes in CMJ concentric variables are likely due to the changes in CMJ eccentric variables (Cormie et al., 2010). Similarly, Gathercole et al. (2015d) reported significant improvements in both concentric and eccentric CMJ variables after completing a 19-week training program. The authors detected a very large decrease in the duration of the eccentric phase of the CMJ, which along with increases in force at zero velocity, area under the force-velocity curve, and mean power across the eccentric and concentric phases point to a change in CMJ movement strategy. Since the above studies point to positive adaptations in the CMJ eccentric phase from training, it may be possible that an alternative movement strategy exhibiting less favorable changes in eccentric CMJ variables are sensitive to NMF. However, since a deeper dip has been shown in fatigued (Legg et al., 2017) and enhanced (Cormie et al., 2009) performance states, it is unknown what is the change in CMJ movement strategy for a fatigued athlete.

In summary, CMJ performance is useful to monitor for NMF. Concentric and eccentric variables can be used to monitor NMF over the course of hours, days following competition, or over a training period/season. Changes in the eccentric portion of the CMJ during periods of fatigue suggest that movement strategy may change when fatigue is present. Therefore, along with concentric-only CMJ measures, variables that incorporate the eccentric phase may be important to consider when monitoring NMF.

Subjective Measures

Training imposes stress on athletes that affects their physical and psychological well-being, that when not noticed or ignored, could progress from acute fatigue to over-reaching, and in more advanced levels, to the overtraining syndrome (Saw, Main, & Gastin, 2015). Psychological signs such as mood disturbances and symptoms similar to clinical depression have been observed in athletes progressing through the aforementioned stages of training fatigue (Morgan, Brown, Raglin, O'Connor, & Ellickson, 1987). Although actual sport performance is likely the best indicator of the ability to perform, it is impractical to physically test on a daily basis to determine the state of readiness for most sports or events. A tool that has been used to aid coaches and researchers to identify athletes that may be in a lower level of athlete readiness are questionnaires that allow self-reporting of signs and symptoms of physical and psychological fatigue. These signs and symptoms, collectively referred to as "subjective measures", lead to athletes reporting perceived changes in well-being (Saw et al., 2015).

There have been several self-report questionnaires designed for monitoring subjective measures of well-being, where some are utilized on a daily basis and others multiple times per week by high performance coaches (Taylor et al., 2012). While a number of extensive psychological profile surveys exist, such as the Recovery-Stress Questionnaire for Athletes (Martinent, Decret, Filaire, Isoard-Gautheur, & Ferrand, 2014), Profile of Mood States (Schmikli, De Vries, & Backx, 2010), and Daily Analysis of Life Demands (Storey, Birch, Fan, & Smith, 2016), the most commonly used self-report surveys were custom-designed forms that typically use 4 - 12 items measured on a Likert scale ranging from 1 - 5 or 1 - 10 (Saw et al., 2015; Taylor et al., 2012). Muscle soreness, perception of fatigue, sleep duration and quality, stress, and mood are frequently considered important indicators of an athlete's state of recovery and readiness (McLean et al., 2010; Saw et al., 2015; Taylor et al., 2012; Twist, Waldron, Highton, Burt, & Daniels, 2012; Wellman, Coad, Flynn, Climstein, & McLellan, 2017a). Self-reported subjective measures have been shown to be more sensitive and consistent when monitoring fatigue compared to other more objective measures, such as physical performance tests and blood markers (Saw et al., 2015). In addition, subjective measures are noninvasive, low-cost, and efficient to administer (Main & Grove, 2009). A potential limitation may be the concern from some coaches, who suspect that athletes may purposely score the questionnaires poorly in order to reduce the prescribed workloads in training sessions (Meeusen et al., 2013).

Some subjective measures have high sensitivity to impaired well-being following acute training loads and competition, while others do not (Johnston et al., 2013; McLean et al. (2010); Saw et al., 2015; Twist et al., 2012). McLean et al. (2010) monitored subjective wellness variables and CMJ performance several times during inter-match microcycles in a professional rugby season. The day after matches showed a decrease in CMJ performance compared to a preseason baseline. At the same time-point, overall well-being, muscle soreness, and fatigue ratings were also significantly worse than their pre-match scores. Conversely, there were no significant changes in ratings of stress levels, mood, and sleep quality reported. Other rugby studies demonstrated similar decrements in CMJ performance after matches that coincided with less favorable scores for overall well-being (Johnston et al., 2013), muscle soreness, (Johnston et al., 2013;

Twist et al., 2012), and perception of fatigue (Twist et al., 2012), with no significant changes in sleep quality, stress levels, and mood reported (Johnston et al., 2013).

Subjective measures have been useful during longitudinal monitoring at well. McGuinness et al. (2018) compared distances covered and subjective wellness variables during a seven-game, two-week international-level field hockey tournament. The relative distance covered at high-intensity speeds per game progressively declined from match to match over the course of the tournament. During the tournament, muscle soreness levels, recorded the day of each match prior to competition gradually became worse over games 2 - 7 compared to game 1. However, total distance covered during each match stayed relatively the same. Therefore, the decline in relative high-intensity distance, increase in muscle soreness, and similar total distance scores in each match suggests there was an accumulation of fatigue throughout the tournament. Stress levels and mood, when compared to game 1, were worse for some (but not all) of the remaining six matches, so these wellness variables may not be as sensitive as muscle soreness is to changes in NMF.

To summarize, subjective measures have been used to monitor NMF in athletes from training and competition loads. Some measures, such as perception of fatigue, muscle soreness, and overall well-being, seem to be more sensitive to changes in NMF, while others are not. While both CMJ tests and subjective questionnaires detect NMF, understanding how the amount and intensity work performed during exercise is related to NMF is essential to help peak athletes for competitions. Thus, methods for tracking this quantification of work will be explored in the next section.

MONITORING TRAINING LOADS

To prepare for competition, athletes undergo rigorous training. The goal of training is to stimulate positive adaptations in the human body so athletes improve and are ready to perform at their best on game day. The product of volume and intensity is commonly referred to as training load. The ability to monitor training loads can help manage fatigue and help reveal needs for change in volume and/or intensity within the training program. During training, athletes perform a prescribed external training load (ETL) (i.e. physical work accomplished), which are usually measured in terms of speed, power output, distance travelled, etc. (Bourdon et al., 2017). The physiological or perceptual responses that result from the ETL make up an internal training load (ITL) (Gabbett, 2016). Physiological responses include heart rate, blood lactate, oxygen consumption and others, while perceptual responses include rating of perceived exertion and subjective measures of wellness. It has been suggested that the ITL resulting from the ETL stimulate the training adaptations that affect performance (Impellizzeri, Rampinini, Couttts, Sassi, & Marcora, 2004). Therefore, the combination of the applied external and resulting ITL determines the training outcome (Gabbett, 2016).

There are instances when training loads are not optimal, which can lead to negative consequences. Extremely excessive loads during a training period, with insufficient time for recovery, lead to chronic fatigue and attenuated performance (Coutts, Slattery, & Wallace, 2007; Coutts & Reaburn, 2008; Johnston et al., 2013). While there is a lack of consistent terminology describing the severity and duration of these performance decrements, Meeusen et al. (2013) separates performance decrements into three categories. Functional overreaching (FOR) takes place when an accumulation of stress and fatigue causes short-term decrements in performance, with or without signs of psychological and physical maladaptation, where several days or a few weeks are required for complete recovery (Halson & Jeukendrup, 2004; Meeusen et al., 2013). Once fully recovered, athletes typically experience a "supercompensation" effect, where performance is improved (Chiu & Barnes, 2003). However, if athletes continue intense training without adequate recovery following FOR, they may evolve into a state of non-functional overreaching (NFOR) characterized by a stagnation or decrease in performance (Meeusen et al. 2013), where recovery may take several weeks or months. At the NFOR stage, signs of severe fatigue and training distress, such as psychological (e.g. perceptions of fatigue) and hormonal disturbances occur. If intense training persists, where athletes do not allow for recovery from NFOR, overtraining syndrome (OTS) may develop (Meeusen et al. 2013). With OTS, performance decrements take several months to years to achieve full recovery (Halson & Jeukendrup, 2004; Meeusen et al., 2013). Likewise, excessively low of training loads, or undertraining, leads to inadequate overload to produce a training effect, producing poor performance (Chiu & Barnes, 2003; Halson, 2014). Thus, optimal training loads and sufficient recovery periods are required to improve performance.

Monitoring ETLs during practice through time-motion analysis in team sports is used to quantify the physical demands required by athletes during competition (e.g. sprinting, accelerations and decelerations, jumps, etc.). Although scientists and coaches have used video to quantify ETLs in the past, time-motion analysis using video is not very practical due to their labor-intensive nature, limiting the sample size (King, Jenkins, & Gabbett, 2009). In recent years, the incorporation of global positioning systems (GPS) affixed to an athletes body has allowed for much larger sample sizes, and distances covered during activities of various velocities can been tracked (Gabbett, 2010; Gentles, Coniglio, Besemer, Morgan, & Mahnken, 2018; Wellman et al., 2017a). Unfortunately, GPS has its drawbacks. Monitoring using GPS cannot be done indoors, and partial signal obstruction by surrounding structures and clouds may produce position readings that are off by ± 5 meters, so values may be unreliable over short distances (Cardinale & Varley, 2017; Duncan, et al., 2012). Furthermore, as velocity of locomotion increases, GPS error increases, in part due to the inaccuracies in position readings (Johnston et al., 2012). Additionally, GPS devices do not accurately monitor activity that occurs in small areas, such as an offensive lineman pass blocking, as there is little horizontal locomotion, yet intense activity occurs (Cardinale & Varley, 2017).

Integrated triaxial accelerometers (TA) have also been shown to be both reliable and valid when it comes to monitoring ETLs (Boyd, Ball, & Aughey, 2011; Gabbett, Jenkins, & Abernethy, 2010; Johnstone et al., 2012; Scott, Lockie, Knight, Clark, & Janse de Jonge, 2013). Gravitational forces (g-forces) are tracked by TAs, both in number and magnitude in three dimensions (i.e. frontal, sagittal, and transverse axes). Triaxial accelerometers measure the changes in g-forces on the body during all modes of movement, such as walking, running, sprinting, as well as changes in direction and jumping, which tend to have relatively lower g-force values (5 – 6) (Wellman et al., 2017b). In addition, TAs measure the forces from the collision of bodies, which have relatively higher g-force values (6.1 – 10) (Wellman et al., 2017b). As a result, TAs give an indication of musculoskeletal stresses during training and competition (Gentles et al., 2018; Vanrenterghem, Nedergaard, Robinson, & Drust, 2017). Additionally, unlike GPS, TAs can be used indoors (Aoki et al., 2017; Cardinale & Varley, 2017). Triaxial accelerometers can monitor g-forces from all athletic actions that occur, including those in place (e.g. throwing, blocking), while GPS cannot (Cardinale & Varley, 2017; Hulin, Gabbett, Johnston, & Jenkins, 2018; Ward, Ramsden, Coutts, Hulton, & Drust, 2018). Further, the training load data accumulated from TAs provides a good indication of the volume and intensity of locomotion and have a strong relationship to total distance covered determined by GPS (Gentles et al., 2018; Polglaze, Dawson, Hiscock, & Peeling, 2015). Therefore, TAs overcome many of the shortcomings of GPS devices and may be more beneficial when monitoring ETLs in some sports (Cardinale & Varley, 2017).

There are two common metrics used to report TA training loads in the literature, PlayerLoad (PL) and Mechanical Load (ML), although a direct comparison of the two has not been reported. PL is calculated as the square root of the sum of the instantaneous rates of change in g-force values in all three dimensions over the course of one second. Since TAs calculate the average of 100 g-force values in each of the three-dimensions every second (100 Hz), there is division by 100 (see Equation 1) (Boyd et al., 2011).

$$PlayerLoad = \sqrt{\frac{\left(a_{y1}-a_{y-1}\right)^2+(a_{x1}-a_{x-1})^2+(a_{z1}-a_{z-1})^2}{100}} \qquad (1)$$

Mechanical Intensity (MI) is the peak g-force value within all three dimensions taken over the course of each second sampled at 100 Hz. The peak g-force value is assigned a value on a linear scale of 0-10, where 0.5 g-forces equals 0, and > 6.0 g-forces equals 10. The sum of all the products of MI and epoch duration is ML (see Equation 2) (Zephyr Technology, 2016).

$$Mechanical\ Load = \sum_{e=1}^{n}(Mechanical\ Intensity * Epoch\ Duration) \quad (2)$$

While the equations for both PL and ML are slightly different, the information about ETLs are similar, as both accelerometer-based loads sum all the three-dimensional instantaneous rates of change in g-force values to give a value to the total amount of work done. PlayerLoad has shown good correlations in team sports with total distance travelled (r > 0.67) (Casamichana & Castellano, 2015; Casamichana, Castellano, Calleja-Gonzalez, San Román, & Castagna, 2013; Malone, Hughes, Roe, Collins, & Buchheit, 2017). In addition, to get a more comprehensive picture of total training volume, TAs take into account the frequency and intensity of body collisions. If the athlete's position in the sport involves many collisions between bodies, the correlation between total distance and PL becomes stronger (Gabbett, 2015). Amongst football position groups, Ward et al. (2018) reported that while some groups covered significantly greater distances and had less contact (e.g. wide receivers) than other positions (e.g. offensive linemen), those groups did not necessarily have a corresponding larger PL value. Thus, accelerometer-based load is a good indicator of the total ETL an athlete experiences during practices and competitions. How training loads affect CMJ and subjective wellness data will be discussed in the next four sections.

Effects of Training Load on Jump Performance

Decreases in CMJ performance from excessive ETLs have been shown in team sports (Cormack et al., 2008b; Johnston et al., 2013; Roe et al., 2017). For example, significant inverse correlations were shown between PL of the previous practice and CMJ power (r = -0.65) and jump height (r = -0.67) during a 5-week college basketball preseason training period (Heishman et al., 2018). Likewise, Roe et al. (2017) detected a decline in CMJ performance when training loads progressively increased and improved when training loads were reduced over an 8-week rugby training period. Similar impairments in CMJ performance have also been observed during the competitive rugby period after strenuous matches (Cormack et al., 2008b; Johnston et al., 2013), which makes sense, since competitions have been shown to have higher ETLs than in-season practices (Henderson, Cook, Kidgell, & Gastin, 2015; Montgomery, Pyne, & Minahan, 2010; Wellman, Coad, Flynn, Siam, & McLellan, 2019a). Therefore, the previously described literature supports the hypothesis of excessive, chronic ETLs may cause NMF to be exhibited in athletic performance variables.

Recovery of Jump Performance after Competition

Monitoring performance over consecutive days following a fatiguing task (e.g. competition) gives sport scientists or coaches a better perspective of the recovery rate of many CMJ variables (Cormack et al., 2008a; Gathercole et al., 2015b; McLean et al., 2010; McLellan & Lovell, 2012). Cormack et al. (2008a) noted that CMJ performance variables including flight time, FT:CT, and mean power, were substantially lower 24 hours post-match compared to pre-match values in Australian Rules football players. All variables showed improved recovery to varying degrees 72 hours post-match, but mean power and mean power relative to bodyweight were still substantially lower than pre-match values. At 96 hours post-match, all variables returned to pre-match levels. Rugby athletes also have shown CMJ variables return to baseline within 3 - 6 days after matches (McLean et al., 2010; McLellan and Lovell, 2012).

Longitudinally, over an entire season, CMJs have been used to monitor an accumulation of NMF (Cormack et al., 2008b; Kraemer et al., 2004; Hills & Rogerson, 2018). Using loaded CMJs, Hills and Rogerson (2018) observed peak velocity fluctuate and consistently decline throughout a 12-week in-season period. While no negative trend in CMJ performance were observed across an entire 22-match Australian Rules football season, Cormack et al. (2008b) observed portions of the season where FT:CT was substantially less 3 - 6 days post-match, including after three of the first six matches. Similarly, Kraemer et al. (2004) detected fluctuations in CMJ jump height throughout an 11-week collegiate soccer season, with starters suffering a significant drop from preseason baseline value in week 9. Thus, CMJ performance may be a good method of tracking NMF during the competition phase for team sports.

Effects of Training Load on Subjective Measures

It is typically recommended to collect ITL data alongside ETL data to get a full picture of the workload-response relationship during training and competition (Halson, 2014; Gabbett, 2016). Questionnaires assessing subjective measures is one method of monitoring ITL that has demonstrated an impairment of perceived well-being with an acute (Malone et al., 2017; McLean et al., 2010; Wellman et al., 2017a), and chronic increase in training load (Gastin, Meyer, & Robinson, 2013; Johnston et al., 2013; McGuinness et al., 2018; McLean, Petrucelli, & Coyle, 2012). During a 7-day preseason Gaelic football training camp, Malone et al. (2017) monitored ETL (high-speed running distance) and wellness variables, including muscle soreness and fatigue, during each training session. It was observed that during the training camp, player's daily wellness measures significantly fluctuated from the start to the end of the 7-day period. In addition, daily fluctuations in total running distance were strongly related ($r = 0.68$) to daily changes of overall wellness scores. Therefore, the authors concluded that the scores on simple wellness questionnaires were sensitive enough to detect daily changes in training load and therefore, are useful in organizing training intensity and volume between competitions. Likewise, Wellman et al. (2017a) monitored ETL variables and perceived wellness data during NCAA Division I football preseason practices. When perceived muscle soreness and fatigue scores were less favorable, ETL variables (e.g. PL, total distance) were significantly higher during the previous training day. In addition, with evidence that competitions have higher training loads than in-season practices (Henderson et al., 2015; Montgomery et al., 2010; Wellman et al., 2019a), wellness scores are also less favorable within 24 hours after team sport games (Johnston et al., 2013; McGuinness et al., 2018; McLean et al., 2010; Twist et al., 2013; Wellman, Coad, Flynn, Siam, & McLellan, 2019b). In summary, the above studies demonstrate a relationship between changes in training loads and subjective measures of wellness, so psychological and physiological questionnaires may be useful when monitoring NMF.

Recovery of Subjective Measures after Competition

Subjective measures of wellness have been shown to progressively recover after competition in team sport athletes (Coutts & Reaburn, 2008; Coutts et al., 2007; Fullagar, Govus, Hanisch, & Murray, 2017; Gallo, Cormack, Gabbett, & Lorenzen, 2017; Gastin et al., 2013; McLean et al., 2010; McLean et al., 2012). For example, over the course of a 16-week collegiate soccer season, McLean et al. (2012) noted weekly perceptions of fatigue, muscle soreness, and overall well-being were restored from the second to the fifth day following a match. Consequentially, starters reported more muscle soreness throughout the season and took longer to recover following a match than non-starters. The authors attributed the longer recovery time to the difference in weekly loads accounted for by increased stress from match play. Collision team sports, like Australian Rules football and American football, also showed significant, steady improvement in perceptions of fatigue, muscle soreness, and overall well-being toward baseline values in the 4 - 6 days after games (Gastin et al., 2013; Fullagar et al., 2017).

To analyze the relationship between objective and subjective measures of fatigue, McLean et al. (2010) observed both CMJ performance and wellness measures in the days subsequent to rugby matches. Perceived fatigue, muscle soreness, and overall well-being significantly improved over the four days following a rugby match, which paralleled the recovery in CMJ flight time and relative power. Since other studies have also shown that CMJ scores take at least 3 days to return to baseline after competition (Cormack et al, 2008a; McLellan & Lovell, 2012), wellness questionnaires may also be good tools to monitor NMF (McLean et al., 2010). In addition, since wellness questionnaires are excellent tools to detect NMF because they are not invasive, inexpensive, and are simple to administer (Main & Grove, 2009).

Longitudinally, subjective measures of wellness have been tracked for entire seasons in team sports (Gastin et al., 2013; Fullagar et al., 2017; Hills & Rogerson, 2018; McLean et al., 2012). Gastin et al. (2013) noted perceptions of fatigue, pain/stiffness, and well-being gradually regressed in Australian Rules football players. However, during weeks 14 and 26, the authors noted perceptions of fatigue and overall well-being scores recuperated when there was no competition the previous week, with fatigue showing significant improvement. While training loads were not specifically measured, this spike toward more favorable wellness scores gives evidence that acute reductions in training loads may help athletes recover from fatigue. Hills and Rogerson (2018) reported comparable results to Gastin et al. (2013) in professional rugby players, with overall well-being scores deteriorating across the 12-week season. There was a significant improvement on week 12, which the authors attributed to no match being played the previous week (Hills & Rogerson, 2018). Other team sport studies (Fullagar et al., 2017; McLean et al., 2012) noted fluctuations in wellness scores, but did not observe negative trends in wellness scores across their competition seasons. The authors proposed this lack of change in subjective measures of wellness might have been due to coaches reducing training loads to avoid an accumulation of NMF (Fullagar et al., 2017; McLean et al., 2012). Therefore, since wellness variables have similar time-course of recovery as CMJ variables, they may be useful to monitor NMF in the days following competitions and throughout an entire season.

Summary of Monitoring Training Loads and their Dose-Response Relationship to Jump Performance and Perceptions of Wellness

In conclusion, monitoring external and ITLs allow coaches and sport scientists to be aware of unwanted NMF in order to peak athletes' performance at appropriate times. There are a variety of ways to determine ETL, with TAs possibly being more useful than GPS for sports that have a number of movements in a small space, change direction or accelerate and decelerate often, and especially if they train or compete indoors. Player Load and ML are two metrics determined by TAs where the total ETL can be quantified over the course of a training session or competitive match. Consequently, these ETLs have an impact on ITLs. Subjective measures, such as wellness questionnaires, are reliable tools that can monitor the influence ITLs have on NMF. When training loads are excessive, decrements in sport performance and changes in well-being are evident. Thus, care must be applied when prescribing training volume and intensity so that performance can be maximized at the appropriate time of the sport season. Specifically, the physical demands of American football will be described in the next section.

FOOTBALL TRAINING DEMANDS

American football is a collision sport that requires short, repeated bouts of high-intensity exercise (Iosia & Bishop, 2008; Rhea et al., 2006; Wellman et al., 2017b). Players at different positions cover a variety of distances at different speeds in practices and games (DeMartini et al., 2011; Wellman et al., 2017a; Ward et al., 2018). In addition, rapid accelerations and decelerations, as well as sport-specific actions (e.g. blocking, tackling), contribute to the physical demands accumulated by football players (Sanders, Roll, Peacock, & Kollock, 2018; Wellman et al., 2017b). To prepare for competition loads, training intensity, duration, and recovery must be periodized over the course of a practice week so that the athletes are prepared for games (Rhea et al., 2006; Sanders, Roll, & Peacock, 2017; Wellman, Coad, Goulet, & McLellan, 2016).

Football teams are made of players that specialize in a variety of positions, each of whom require unique physical and physiological characteristics to be successful (Pincivero & Bompa, 1997). The players that have positions on “offense” participate when their team has the ball. The goal of the offense is to move the ball forward to score points. Positions on offense include offensive linemen (OL), quarterback (QB), running back (RB), tight end (TE), and wide receiver (WR) (Pincivero & Bompa, 1997; Ward et al., 2018). Each position has different responsibilities for the offense to be successful. The OL’s job is to block opposing players and move them out of the way in order to prevent the ball carrier or passer from being tackled (DeMartini et al., 2011; Wellman et al., 2016; Wellman et al., 2017b). Quarterbacks run with the ball or throw it to WRs, RBs, or TEs (Wellman et al., 2017b). Wide receivers predominantly run pass routes and catch passes, but they are also expected to block opponents (Wellman et al., 2017b). Tight ends have a combination of OL and WR duties, as they are expected to block (primarily DL and LBs) and run shorter pass routes downfield than WRs (Pincivero & Bompa, 1997). Along with their pass blocking (primarily DL and LBs) and short pass route responsibilities, RBs are the primary ball carriers (Wellman et al., 2017b). A special kind of RB is called the fullback (FB), who tends to carry the ball less often and blocks more often than other running backs (Mallory, Nehlen, & American Football Coaches Association, 2006).

When their team does not have the ball, different players are used to prevent the opposing team's offense from moving the ball and scoring. These are players that are on "defense" and include the following positions: defensive linemen (DL), linebacker (LB), and defensive back (DB) (Pincivero & Bompa, 1997; Ward et al., 2018). Defensive linemen engage with the OL near the line of scrimmage, explosively pushing and pulling in order to move the OL out of the way so they can tackle the ball carrier or passer (Pincivero & Bompa, 1997; Sanders et al., 2017). Defensive backs guard any offensive player (primarily WRs) that goes out for a pass, but they are also expected to help tackle ball carriers on running plays (Wellman et al., 2017b). Linebackers are also responsible for guarding offensive players on their pass routes (primarily RBs and TEs), but LBs have a greater responsibility to tackle the ball carrier on running plays when compared to DBs (Pincivero & Bompa, 1997; Wellman et al., 2017b).

Due to their differences in body mass and the types of physical activities they perform, offensive and defensive positions can be grouped together as linemen, which includes OL and DL, or non-linemen, which includes WRs, DBs, RBs, QBs, TEs, FBs, and LBs (DeMartini et al., 2011). Linemen have much greater body masses than non-linemen so they can effectively hit, block, and/or tackle (Pincivero & Bompa, 1997). Non-linemen are smaller than linemen in order to move faster and change directions quicker in in order to carry the ball, run pass routes, cover receivers, and/or tackle the ball carrier in open space (Pincivero & Bompa, 1997). In addition, TEs, and LBs may be larger than WRs, DBs, and RBs, due to frequent hits when blocking and tackling on running plays (Pincivero & Bompa, 1997; Wellman et al., 2017b). To group the non-line position players by responsibilities and size, the WRs, DBs, and RBs are typically classified as "skill" positions, while FBs, TEs, and LBs may be classified as combination, or "combo" positions.

Positional differences account for greater distances covered when jogging, running, and sprinting for skill and combo positions compared to linemen during football games (Sanders et al., 2017; Wellman et al., 2016) and practices (DeMartini et al., 2011; Wellman et al., 2017a). More specifically, skill positions cover more total distance and distances at all different speeds than combo positions (Sanders et al., 2017; Wellman et al., 2017a; Wellman et al., 2016). Skill positions reach high speeds by running and covering pass routes 20 - 40 yards down field, and jog back that same distance at light to moderate speeds to the line of scrimmage (Rhea et al., 2006). Conversely, linemen cover less total distance and distances at different speeds than combo positions (Sanders et al., 2017; Wellman et al., 2017a; Wellman et al., 2016). Linemen do not have enough distance to reach high speeds, as they line up about 1 meter across from their opponent (Wellman et al., 2016). With so many collisions when hitting, blocking, and tackling, linemen do not often travel very far from the line of scrimmage, allowing them to walk back to their starting spots between plays (Rhea et al., 2006). Total distance traveled for combo players fall between skill and linemen because they sometimes carry the ball, run pass routes, and/or cover receivers (similar to skill position). Yet, on other plays, they are expected to hit, block, and/or make tackles close to the line of scrimmage (similar to linemen) (Pincivero & Bompa, 1997; Sanders et al., 2017, Wellman et al., 2017a).

Skill positions accumulate more acceleration and deceleration efforts (Sanders et al., 2018; Wellman et al., 2016) and cover greater distances (Wellman et al., 2017a) at different intensities than combo. On the other hand, linemen accumulate fewer acceleration efforts (Sanders et al., 2018; Wellman et al., 2016) and cover less distances (Wellman et al., 2017a) at all different intensities than combo positions. The reason combo positions' acceleration efforts and distances travelled fall in the middle is due to the shared responsibilities combo have with both skill positions and linemen (Pincivero & Bompa, 1997; Sanders et al., 2017, Wellman et al., 2017b). Interestingly, Sanders et al. (2018) noted that OL had greater deceleration efforts at all different intensities when compared to TEs and RBs, which may be due to the decelerative nature of pass blocking on DL and LBs (Wellman et al., 2017b).

The number and intensity of "impacts", or g-forces accumulated from movement in all 3 planes and the collision of bodies, have been shown to be different between position groups in football games (Wellman et al., 2017b) and practices (Ward et al., 2018; Wellman et al., 2017a). During a professional football preseason training camp, Ward et al. (2018) detected that linemen performed more total high intensity impacts (acceleration above 3.5 m/s^2) than combo players, which can be attributed to the emphasis of hitting, blocking, and tackling in linemen. Wellman et al. (2017b) reported similar results in collegiate football games, as DL accumulated more moderate and heavier intensity impacts (6.6 - 10 g) than LB and DB. However, OL had similar moderate and heavy impact (6.6 - 8 g) profiles to WRs and TEs, and all three position groups had a greater number of moderate and heavy impacts when compared to RBs. This may be due to the collisions RBs and OL accumulate while blocking defensive players and/or being tackled. Since they are the primary ball carriers, RBs had the greatest amount of severe impacts (> 10 g), since many high-velocity impacts occur when being tackled by defensive players or by changing directions quickly. Skill players had a greater number of lighter impacts than their respective offensive or defensive counterparts (5 – 6.5 g). Since lighter impacts are associated with walking and running (Wundersitz, Gastin, Robertson, Davey, & Netto, 2015), and skill players cover more distances at low, medium, and high speeds (Wellman et al., 2016), it makes sense these two positions have more lighter impacts.

The total accelerometer load (i.e. PL, ML) takes into account all the impacts accumulated over a practice or game and their magnitudes, whether they come from running, jumping, changing direction, colliding, or tackling (Ward et al., 2018). Studies have shown positional differences in both football games (Ward et al., 2018; Wellman et al., 2017a) and practices (Sanders et al., 2018) when it comes to total accelerometer loads. Ward et al. (2018) reported that PL was the greatest in WRs and DBs when compared to the other position groups during professional football preseason practices.

However, the authors noted that some positions had relatively higher PL even though they did not cover as much distance. For example, there was a large gap in total distance covered but only a moderate separation in PL when comparing WRs to OL and LBs to DBs. Wellman et al. (2017a) noted similar results during college football preseason practices. The gap between WRs and other offensive players, as well as DBs and other defensive players, was much larger when looking at the total distance covered compared to PL. Since football is a collision sport (Wellman et al., 2017b), and changes in accelerometer load and total distance covered is not proportional (as shown in the previous studies), accelerometer load may be a better indicator of the total amount of physical stress accumulated from practices and games.

To prepare for the physical demands of weekly collegiate football games, week-long practice microcycles are periodized in such a way so that performance peaks on the day of competition, usually on Saturday. A typical practice starts with a warm-up period, followed by "position drills" where players are split up into their different position groups to perform position-specific skills, and practice typically ends with "team" drills, where some or all the position groups of offense and defense come together to perform activities against each other (DeMartini et al., 2011). While few studies have monitored training load trends during in-season weekly practices, a few indicate that the highest loads tend to be on Tuesdays with a declining load every practice until the Saturday competition (Ward et al., 2018; Wellman et al., 2019a). The attenuation in training loads is in part is due to the gradual decline in practice duration over the same time-frame (Wellman et al., 2019a).

SUMMARY OF REVIEW

As previously discussed, acutely lowering practice training loads has been shown to improve perceptions of wellness in team sports (McLean et al., 2010; Wellman et al., 2017a). In addition, improved performance test scores, such as CMJ variables, demonstrate this reduction in NMF (Cormack et al., 2008a; Gathercole et al., 2015b; McLean et al., 2010). Therefore, properly periodizing weekly microcycles is essential to peak football players for maximal performance on game day.

Unfortunately, few studies are available that quantify and compare the changes in daily ETLs at practices during a football season (Wellman et al., 2019a). Wellman et al. (2019a) observed that practice PLs were approximately the same on Tuesdays and Wednesdays, with a decrease in PL on Thursdays in preparation for Saturday games (Wellman et al., 2019a). PL was lower during the last few weeks of the season on Tuesdays and Wednesdays, which the authors attributed to coaches naturally lowering practice training loads to prevent an accumulation of NMF (Wellman et al., 2019a). In addition, no measures for monitoring NMF were used in this study, nor were practice training loads included for their lighter practice training load days. Therefore, there is a need in the literature for a comprehensive analysis of an American football season. This thorough analysis should include daily monitoring of practice training loads, along with assessing NMF through objective and subjective measures multiple times per week.

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