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by
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Keywords: women's basketball, countermovement jump, workload, preseason

ABSTRACT

Monitoring External Workloads and Countermovement Jump Performance Throughout a Preseason in Division 1 Collegiate Women's Basketball Players

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Monitoring external workloads and countermovement jump performance may be useful for coaches. **PURPOSE**: The purpose of this study was to determine the effects of external load on player performance as measured by a CMJ and specific blood biomarkers throughout the preseason. **METHODS**:10 female division 1 basketball athletes had PlayerLoad^{TM} (PL) monitored for all mandatory basketball training during six weeks of the preseason and CMJs were performed weekly. Blood biomarkers were collected before preseason and at the end of preseason. Data were analyzed via the Catapult Sport software (Openfield, Catapult, Innovations, Melbourne, VIC, Australia) to quantify all participant movement. Data from CMJs were analyzed via Sparta Science technology (SpartaTrac; SPARTA Performance Science, v1.2.4). Cumulative effect of physical activity (CTPL) was estimated as a sum of total PL up to each jump testing session divided by the number of days. Linear mixed-effects models were used to model data related to the efficacy of PL and CTPL. Athletes (id) and their positions were examined as potential random effects. **RESULTS**: The best fit model suggested a high-order polynomial pattern between PL and the number of days since the first jump testing session with a random effect for the intercept (marginal $R^2 = 0.290$; conditional $R^2 = 0.471$). The fixed effect for the slope of the first order term was found to be positive. There was a significant negative effect of CTPL on JH ($p = 0.0037$). The boot strapped model showed a marginal R2 of 0.0183 (95% CI [0.000952, 0.0744]) and a conditional R2 of 0.884 (95% CI [0.762, 0.956]). For RSI_{mod}, a significant negative association between RSI_{mod} and CTPL ($p = 0.0039$, 95% CI [-0.0002214, -4.597081e-05]). **CONCLUSION**: Workloads increase during preseason. CMJ height and RSI_{mod} may have limited utility in displaying the effects cumulative workloads. Position played did not impact workload or the impact of that workload on the player. **PRACTICAL APPLICATION**: Cumulative effect of physical activity may be tracked using CTPL derived from PL. Practitioners may be encouraged to monitor alternative countermovement variables to better understand performance response to the cumulative effect of physical activity.

DEDICATION

This dissertation is dedicated to all the female athletes overlooked for research.

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Thanks to the Women’s Basketball players for showing up every day ready to work and remembering to wear the polts.

Lastly, thanks to my mom. You’re the real MVP.

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Chapter 1. Introduction

The monitoring of external workloads and how those external workloads impact countermovement jump performance has been used across multiple sports (Aoki et al., 2016; Edwards et al., 2018; Ferioli, Bosio, Bilsborough, Torre, et al., 2018; A. Heishman et al., 2020; Nunes et al., 2014; Sams et al., 2018; Spiteri et al., 2013). External workload can be defined as the mechanical or locomotive strain that an athlete generates during activity, resulting in psychophysiological stress (A. D. Heishman et al., 2018; Impellizzeri et al., 2019; S. Malone et al., 2017). Manipulation of external workload variables can be accomplished when planning the training process, which ultimately dictates the quality and quantity of the external workload generated by the athletes in training (Booth & Thomason, 1991; A. D. Heishman et al., 2018; Impellizzeri et al., 2004, 2005, 2019). Positive adaptations to prescribed external workloads are the foundation to an effective training program in sport (Stone et al., 2007). Because the manipulation of external workloads is imperative for a successful long-term training plan, the desire to monitor and measure these loads should also be thought of as an imperative part of a successful long-term training plan.

The use of wearable technology to monitor and measure external workloads has been carried out previously within team sport (Aoki et al., 2016; A. Heishman et al., 2020; A. D. Heishman, Curtis, et al., 2018; Lukonaitienė et al., 2020; Petway, 2022; Ransdell et al., 2020; Sanders et al., 2021; Staunton et al., 2018; Towner et al., 2023; Vazquez-Guerrero et al., 2020). Several notable outcomes of these observations have been noted. For example, scholarship male basketball athletes had substantially higher weekly “Player Loads” than walk-ons during a pre-season period (Heishman et al. 2020). Interestingly, statistically significant variations in external workloads, as measured by PlayerLoads, occurred across 4 seasons in elite women’s collegiate basketball (Ransdell et al. 2020). Moreover, a considerable difference in the intensity of these external workloads were noted during losses when compared to wins, with losses having higher IMAs when compared to wins (Ransdell et al., 2020). Lukonaitiené et al. (2020), studying under 18 yrs and under 20 year groups, observed small but statistically significant differences in weekly external workload totals between U18 and U20 national level female basketball players. A within-team analysis indicated statistically significant differences in workload in Under20 and a marked reduction in Week3 (taper period) in the Under18. Pre- post-preparation changes showed Under18 only increased in multi-stage test (YOYO) performance. However, the Under20 group showed statistical improvement in 10-m sprint split time, countermovement jump (CMJ) and YOYO. Lukonaitiené et al. (2020 et al. concluded that a constant but adequate workload appeared to positively alter players' readiness and physical performances during short intensified preparation periods. Conversely, using a high workload with periodization strategies encompassing short overload and taper phases induced positive changes in players' aerobic performance, lower readiness values but no substantial alterations in anaerobic performances.. Lastly, Towner et al. (2023) documented statistically significantly higher external workloads during the non-conference period of a division 1 women's collegiate basketball season compared to pre-season and conference play. Collectively these data indicate that the measurement of external workloads appear to be sensitive enough to detect differences between seasons, season phases, wins and losses, higher and lower playing levels, and between scholarship and walk-ons in basketball athletes. It is apparent that quantification of external workloads via wearable technology can provide valuable insight into how much work an athlete is completing, the efficacy of a training program, and the varying workload requirements experienced at each stage of a season.

Changes in countermovement jump (CMJ) may provide insight as to how an athlete responds to a given training protocol or the readiness level of that athlete following competition in sport (Edwards et al., 2018). Specifically, decreases in CMJ performance may indicate neuromuscular fatigue. Athletes with higher levels of neuromuscular fatigue, as assessed by a CMJ, accumulate less high-speed running distance and experience reductions in acceleration ability which are important in the sport of basketball (Cormack et al., 2013; Stojanović et al., 2018). Furthermore, because the CMJ responds to alterations in physiology, a CMJ could be considered an estimate of internal load (A. D. Heishman et al., 2018; Impellizzeri et al., 2019). Internal training load can be defined as the physiological outcome of the imposed training stimulus and can include hormonal, immunological, or biochemical markers (Alexiou & Coutts, 2008; Booth & Thomason, 1991; A. D. Heishman et al., 2018). Additionally, internal load can represent the psychophysiological strategy or strategies used to cope with external workloads (Alexiou & Coutts, 2008; A. Heishman et al., 2020; A. D. Heishman et al., 2018; Impellizzeri et al., 2019). Because of this, the countermovement jump has been used as a non-invasive method to assess internal stress on an individual basis in a team sport setting (Cormack et al., 2013; Ellis et al., 2022; Ferioli, Bosio, Bilsborough, Torre, et al., 2018; A. Heishman et al., 2020; Hoffman, Fry, et al., 1991; Sams et al., 2018; Spiteri et al., 2013). A. For example, Heishman et al. (2020) noted moderate decreases in Flight Time:Contact Time ratio (FT:CT) and modified reactive strength index (RSI_{MOD}) from a CMJ when increases in PlayerLoad per minute occurred during a collegiate pre-season period. Spiteri et al. (2013) monitored changes in CMJ FT:CT following training sessions and competitions in female basketball athletes. A statistically significant decline in FT:CT was found from baseline to post-game and from pre-game to post-game. In contrast, relative power and jump height statistically significantly increased between post-game and two days post game, respectively. Unfortunately, no mention of external workload measures was made. Sams et al. (2018) found no statistically significant decreases in jump height across a collegiate soccer season, but a moderate practical decrease was noted following the pre-season period. However, a static jump was used throughout the investigation, which may behave differently when fatigue is present when compared to the CMJ (Bobbert et al., 1996; R. J. Gathercole et al., 2015a). Finally, in the sport of basketball CMJ ability can allow for talent identification as higher level players can usually generate higher peak forces, higher absolute peak power, and higher absolute peak force during a CMJ when compared to lower-level players (Ferioli, Bosio, Bilsborough, Torre, et al., 2018; Ferioli et al., 2020a). Therefore, a player's ability to maintain high outputs during a CMJ may be of importance throughout training and competition. Equivocal evidence currently exists when attempting to use a CMJ or only a single metric from a CMJ to assess the implications of external training load in team sport athletes, especially in collegiate women basketball athletes.

The sport of basketball is highly intermittent and a typical game requires over 1,000 movements that last for less than 3 seconds each (Abdelkrim et al., 2007; McInnes et al., 1995; A. Scanlan et al., 2011a; A. T. Scanlan et al., 2015). Characterized as a high intensity sport in which heart rates at 91% of maximal heart rate and blood lactate levels reaching upwards of 6.9 mmol/l during competition have been observed (Abdelkrim et al., 2007; A. T. Scanlan et al., 2012). A large percentage of the highest intensity movements include deceleration during on ball defense, landing, and running. Moreover, front court and back court players have been shown to experience substantial differences in physiological demands, distance covered, and frequency of basketball specific activities during competition or training. Along with the intense physiological and physical demands required during training and competition, the National Collegiate Athletic

Association season lasts 8-9 months for the most successful teams. In addition to those 8-9 months of season, mandatory (≤ 8 hrs for weight-training, conditioning and not more than 4hours of skill-related *instruction* is allowed) training during the summer months is now more common than not. The NCAA does implement weekly hour regulations and require days-off based on the time-point of a season (Towner et al., 2023). Regardless of these regulations, collegiate basketball players are required to take classes, travel to and from competitions, and play multiple competitions within a single week. The reality of basketball season is that it is long and grueling, therefore the appropriate management of external workloads coupled with effective methods to monitor their effects is necessary.

Dissertation Purposes

Therefore, the purpose of this study was to determine the effects of external load on player performance as measured by a countermovement jump and blood borne biomarkers. This was accomplished by:

1. Examining eTL values per session for the entire team and eTL values per session for guards and post player positions (eTL = PlayerLoad).
2. Exploring changes in CMJ performance (Eccentric RFD, RSI modified, Jump Height).
3. Exploring relationships between eTL, countermovement jump performance, and in biomarkers (markers indicative of type II collagen and aggrecan synthesis CPII and CS846 and two markers of type I and II collagen degradation C1,2C and type II only collagen degradation C2C) across ~6 weeks of a pre-season period training phase in Division 1 women’s basketball athletes.

Operational Definitions

PlayerLoad: Using an Inertial Measurement Unit (IMU), “A modified vector magnitude, expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (*x*, *y*, and *z* axis)- and then divided by a scaling factor of 100. PlayerLoad is represented in arbitrary units (AU) (Bredt et al., 2020; Towner et al., 2023)." The formula used for PlayerLoad calculation can be described as follows: the ax_i, ay_i, and az_i are accelerations in their respective plane of motion and $i = 0 \ldots, n$ represents the sampled accelerometer points with $n + 1$ points over the time of the session which is sampled at 100Hz" (Towner et al., 2023 and see https://support.catapultsports.com/hc/en-us/articles/360000510795-What-is-Player-Load).

Cumulative Effect (CTPL): Calculated as the sum of total PlayerLoad up to each CMJ testing date divided by the number of days since the first day of training during the preseason period took place.

Countermovement Jump (CMJ): Athlete starts from fully standing position and initiates downward motion that is immediately followed by an upward motion that leads to a takeoff (Van Hooren & Zolotarjova, 2017). Arm swing is self-selected and not restricted.

Modified Reactive Strength Index (RSI_{mod}): Calculated as jump height divided by time to take off during a countermovement jump ($JH/TTO = RSI_{mod}$ (Ebben & Petushek, 2010).

Eccentric Rate of Force Development (Average Braking Rate of Force Development): Calculated as the difference between the minimum and the maximum force during the eccentric phase of the countermovement jump and measured in N/s units. Measurement starts when force exceeds body weight and ends when velocity reaches zero (Laffaye & Wagner, 2013).

Jump Height (JH): Calculated from flight time ($\text{Flight Time}^2 \times \text{Gravity}/8$) (Personal communication with Sparta Science engineer).

CPII: C-propeptide of type II collagen (CPII) is produced when a C-proteinase cleaves procollagen during formation of fibrils and can be indicative of cartilage collagen synthesis (Krishnan & Grodzinsky, 2018; Månsson et al., 1995).

C2C: C-terminal type II collagen peptide (C2C) can serve as an indicator of collagen degradation as cleavage of type II collagen creates this biomarker (Aurich et al., 2017; Burland et al., 2023; Robin Poole et al., 2004).

CS846: 846 epitope (CS846) is a marker of aggrecan turnover (Aurich et al., 2017; Rizkalla et al., 1992).

Chapter 2. Review of the Literature

Monitoring of external workload and countermovement jump performance may provide valuable insight to how much external workload can affect (Cause and effect) an athlete's ability to produce power. Increasing external workloads has been shown to have negative effects on jump performance in basketball athletes (A. D. Heishman et al., 2018). Because jumping ability is important for performance in basketball, maintaining the ability to produce power throughout an entire season is likely beneficial (Ferioli, Bosio, Bilsborough, Torre, et al., 2018; Ferioli et al., 2020b; A. Scanlan et al., 2011a). Previous examinations of external workloads impact on performance, the specific demands of the sport of basketball, and how specific performance variables respond to various amounts and intensities of external workloads are available in the literature. This literature review is intended to be a thorough review of the available literature regarding those topics.

Demands of Basketball

Basketball is a high intensity intermittent based sport that includes a large amount of lateral movements, multiple changes of direction, jumping power, and the ability to repletely attain high percentage of one's heart rate throughout the duration of a game (N. Ben Abdelkrim et al., 2007; Ferioli, D., Rampinini, E., Bosio, A., La Torre, A., Maffiuletti, 2019; A. D. Heishman et al., 2020; Montgomery et al., 2010; Scanlan et al., 2015; Stojanović et al., 2018). The demands of basketball by position and by quarter will be described below. A combination of research on men's and women's basketball from various levels of play is included in this review.

Abdelkrim et al. (2007) estimated activity patterns and physiological responses over the course of six basketball competitions. Using time-motion analysis, the average frequency for all activities, during a competition, examined was 1050 ± 51 movements with a mean duration of less than 3 seconds for each movement category (Abdelkrim et al., 2007). Additionally, guards had statistically significantly higher frequency and duration of sprint activity, total high intensity activity, medium specific movement activity, and total moderate intensity activity when compared to forwards and centers, respectively. Guards experience higher physical demands during competitions than other positions. During live time, defined as the time during which the game clock was running, and the athlete was on the court, a larger time percentage (44%) was spent either shuffling or participating in any action that was not ordinary walking or running compared to sprinting (5.3%) or low to moderate intensity running (22%). Moreover, standing still and walking comprised 29.9% of the live time. During the final quarter of each competition that consisted of 4 10-minute quarters and a 15-minute half-time break, large decreases were noted for time spent in intense activities. For all positions, percent of live time spent in high-intensity activity during quarter one ranged from 15.61 – 19.18%, whereas percent of live time spent in high-intensity activity during quarter four ranged from 12.49 – 14.29%. Guards had a statistically significant larger percent than centers. This observation indicates that the percentage of time spent in high-intensity activity decreases over the course of a basketball competition.

During competitions, mean heart rate was 171 ± 4 bpm, which was equivalent to 91 ± 2% of maximal heart rate (Abdelkrim et al., 2007) and generally agrees with previous findings (Matthew and Delextrat 2009). Thus, the mean heart rate during a basketball competition can be considered high. Guards experienced a statistically significantly higher mean heart rate during competition (174 ± 4bpm) when compared with the center position (169 ± 3bpm) (ref). Blood lactate concentrations averaged 5.49 ± 1.24 mmol/l during competition, but statistically significant differences were observed at half time (6.95 ± 1.27 mmol/l) versus at full time (4.94 ± 1.46 mmol/l). Blood lactate decreases over the course of a basketball competition, which may be due to the decrease in percentage of time spent in high intensity activities during quarter 4 (Abdelkrim et al., 2007). Once again, statistically significant differences were noted between guards and centers as guards had higher average plasma lactate concentrations (6.36 ± 1.24 mmol/l) than centers (4.92 ± 1.18 mmol/l). These observations suggest guards appear to experience an overall higher physical and physiological demand when compared to centers during basketball competitions. A statistically significant correlation, $r = 0.50$, was observed between blood lactate values and the percentage of time spent in high intensity activity at 5 minutes prior to lactate measurement. Furthermore, basketball can be considered a sport that requires high amounts of short duration movements resulting in heart rates remain relatively high during play. Although blood mean lactate can be considered moderately high, concentrations appear to decrease from half time to full time (Abdelkrim et al., 2007).

McInnes et al. (1995) also used time-motion analysis to classify and quantify movement patterns during basketball competitions as well as assessing physiological demands during the same competitions. Mean frequency of all activities was 997 ± 183 movements with a mean duration of less than 3 seconds of each activity. The frequency of activities recorded during this study is lower than that reported by Abdelkrim et al., (2007). Different level of play, different methods of classifying movements, different styles of play and different length of quarters during competition may explain these differences in frequency of activities. Similar to previously mentioned results, a change in movement occurred every 2 seconds and ~15% of live time was spent in high intensity activity, but no differences in movements were noted between the quarters of play (Abdelkrim et al., 2007; McInnes et al., 1995). An average heart rate during live time was 168 ± 9 bpm, which was the equivalent to 89 ± 2% of HR_{peak} as determined via treadmill VO_2 test. These recorded average heart rates are similar to those reported by Abdelkrim et al. (2007).

Worth noting is that 75% of live time was spent with a HR response of greater than 85% HR_{peak}. Spending large amounts of time with relatively high heart rates has consistently been shown throughout the literature (Abdelkrinm et al., 2007; Mathews & Delextral 2009; McInnes et al., 1995). Blood lactate levels averaged 6.8 ± 2.8 mM, differences in mean values between quarters were not observed. However, as previously noted, statistical differences between quarters during competition has been reported (Abdelkrim et al., 2007). Lastly, moderate to strong correlations were found between blood lactate and both percent of time spent in high intensity activity (r = 0.64) and mean %HR_{peak} (r = 0.45) for the 5 minutes of play prior to blood sampling, which is a higher correlation than what has been previously recorded in basketball athletes during competitions (Abdelkrim et al., 2007; McInnes et al., 1995). The difference in blood lactate correlations may be due to different classification of high intensity activity or due to difference in fitness levels as one study did not report VO_2 max values. Basketball is a sport of large amounts of short duration movements that change at a high rate. Heart rates and blood lactate concentrations throughout live play remain at a relatively high level, which may indicate the need for coaches to prioritize not only anaerobic training, but also aerobic cardiovascular training. Also, worth noting is that anerobic work shows a disconnect between HR and oxygen consumption as HR is likely driven to higher levels by catecholamines and possibly lactate (Treese et al., 1993). Furthermore, there is ample evidence that primarily anerobic training, including interval sprints can improve aerobic power and generally improve cardiovascular function as well as recovery parameters (Patel et al., 2017, Sözen & Akyıldız, 2018); this is an important observation as primarily aerobic work created by repetitive low intensity moments can be detrimental to strength and particularly to RFD (Methenitis et al., 2016; Petré et al., 2023; Wilson et al., 2012).

Because basketball is a team sport that is played at multiple levels (pro, semi-pro, collegiate, etc.) and each player on the team plays a specific position, activity demands may be different between playing levels and playing positions. Scanlan et al. (2011) attempted to describe the activity demands during competition in elite and sub-elite men's basketball athletes. Using video and time-motion analysis, statistically significant activity frequency differences were found between elite and sub-elite backcourt and frontcourt players, respectively. Specifically, at the elite level, a statistically significant higher frequency of standing/walking, jogging, running, sprinting, low-shuffling, upper-body activity, and total movements occurred when compared to the sub-elite level of play. This observation suggest, that players competing at the elite level will experience higher physical demands during competition than players competing at the sub-elite level (A. Scanlan et al., 2011b). The reported frequency of all movements was higher for elite and sub-elite players when compared to previously reported movement frequencies (Abdelkrim et al., 2007; McInnes et al., 1995; A. Scanlan et al., 2011b). These differences may be due to different strategy of game play, different ability level of athletes, and different format of games (10 min quarters vs 12 min quarters). As for distance covered during each movement statistically significant differences were once again noted between elite and sub-elite players. These observations suggest, that for average distance covered, elite level players covered less meters during stand/walk, jog, sprint, and dribble movements when compared to sub-elite players. Frontcourt and backcourt elite level players covered statistically significantly less distance during stand/walk, jog, sprint, and dribble movements when compared to both frontcourt and backcourt sub-elite level players, respectively. For total distance, elite level players covered statistically significantly less distance during stand/walk, sprint, high shuffle, and dribbling ($p < .05$). Elite level backcourt and frontcourt players covered less total distance during stand/walk, sprint, low shuffle, and dribble movements when compared with sub-elite level backcourt and frontcourt players. In contrast, elite level backcourt and frontcourt players covered a substantially higher total distance during jog and run movements when compared to sub-elite level players. This data indicate that, distances covered during movements in a basketball game are dependent upon both level of competition and position played (A. Scanlan et al., 2011b). Understanding the intermittent nature of the game may help coaches organize training to optimize each player's ability.

Another tool that can be used to help quantify specifics of the intermittent nature of basketball is an accelerometer. Using accelerometers placed between the shoulder blades of male collegiate basketball players Koyama et al. (2022) synchronized acceleration data and video images to identify motion and frequency of movements during basketball activities. Each moment that occurred at the 3 different thresholds of >4, >6, and >8 G were extracted for analysis. At 4 G, the highest percentage of observed movements was running (39.7%), deceleration (22.5%), landing (6.4%), and stationary step (5.9%). At 6 G, deceleration (31.9%), running (31.8%), landing (8.0%), and physical contact (7.6%) were the most frequent movements, while deceleration (28.6%), landing (19.5%), running (16.1%), and physical contact (15.9%) made up the most frequent movements at 8 G, respectively. A difference in percent of movements per threshold occurred during basketball, but a special focus on maximizing an athlete's ability to decelerate may be worthwhile for sport coaches. Out of the top 7 movements >6 G extracted by the researchers, deceleration during on-ball defense (45 cases; 0.25 cases $\cdot$ min^{-1}), deceleration during off-ball defense (37 cases; 0.2 cases $\cdot$ min^{-1}), and physical contact during on-ball defense (32 cases; 0.18 cases $\cdot$ min^{-1}) comprised the top 3. It appears that deceleration and defensive movements contribute to the most frequent actions occurring at >6 G in basketball, which may be due to the reactive nature required to play defense. Unfortunately the accelerometers were only worn by male basketball players and these data may not be generalizable to female basketball players as women's and men's basketball have been shown to have notable differences (A. Scanlan et al., 2011b; A. T. Scanlan et al., 2012).

Physiological responses that occur during basketball competitions and training for female athletes is limited. A. T. Scanlan et al. (2012) sought to describe the physiological and activity demands experienced by female basketball players during competition. Using time-motion analysis over the course of 8 competitions, statistically significant differences were noted between halves for standing/walking in both frontcourt players and all players, respectively. For quarters 2, 3, and 4, each half, and the entire game a statistically significant difference in standing/walking and running were seen between playing positions. Specifically, frontcourt players covered statistically significantly greater total distances for standing/walking and running across the first half and entire match when compared with backcourt players. Frontcourt male players have also been shown to cover more total distance for standing/walking and running when compared to backcourt players during basketball competitions (A. Scanlan et al., 2011b). Frontcourt players, independent of sex, will cover more distances for standing/walking and running activities during basketball competition when compared to their backcourt counterparts (A. Scanlan et al., 2011b; A. T. Scanlan et al., 2012). For dribbling activity, the backcourt players had statistically significantly more frequency than frontcourt players, independent of quarter of play ($p < 0.01$). Backcourt players are required to dribble the basketball more frequently than backcourt players regardless of quarter. Statistically significant differences in positional differences were observed for total durations of dribbling activity during each quarter (4), each half, and entire match with backcourt covering more meters than frontcourt (BC: 738 ±

64 vs. FC: 5064 ± 348; $p < 0.05$) , respectively (A. T. Scanlan et al., 2012). For male basketball players, total distance of dribbling activity between backcourt and frontcourt players have not been statistically significant (McInnes et al., 1995; A. Scanlan et al., 2011b). This difference between males and females may be due to women's basketball having distinct positions with distinct roles versus men's basketball having less position specific roles for each player. For heart rate measures, statistically significantly higher absolute (142 ± 10 vs 132 ± 6 bpm) and relative (71.8 ± 5.1 vs 66.7 ± 2.7 bpm) heart rate responses were observed for backcourt players when compared with frontcourt players. Higher absolute and relative heart rate responses in backcourt players may be a result of higher frequency of dribbling activity when compared with frontcourt players. Blood lactate concentrations were not statistically different between frontcourt and backcourt players and values reported in this study are lower than blood lactate values reported previously in male basketball players (McInnes et al., 1995). The difference in reported blood lactate levels may be due to lower reported heart rates in the female basketball players when compared to male players (McInnes et al., 1995; A. T. Scanlan et al., 2012). Lastly, worth mentioning is that all movement frequency of 1750 ± 186 in female players is lower than all movement frequency reported in male players, which has been shown to range from 1050 to 2733 (Abdelkrim et al., 2007; A. Scanlan et al., 2011b). All movement frequency of approximately 997 ± 183 has also been previously reported for male players (McInnes et al., 1995).

The differences in all movement frequencies may be the result of position specific style of play, level of athletes, and competition format, respectively. Overall, backcourt and frontcourt players experience differences in physical demands, physiological demands, skill specific performance demands during basketball and may benefit from position specific training.

Sanders et al. (2021) monitored division 1 women basketball player's heart rate responses during competitions throughout the 5-month season. Athletes wore a microsensor device that included a heart rate strap around their chest during each game. This device measured heart rate responses that were divided into 5 separate zones based on the summated-heart-rate-zone model following collection from each competition (Sanders et al., 2021). VO_2peak and heart rate peak were measured via a laboratory treadmill test prior to the start of the season. Results indicated a statistically significant difference between guards, forwards, and centers across 4 quarters for HR_{avg} ($p = 0.019$), HRpeak ($p < 0.001$), HR_{Zone1} ($p = 0.05$), HR_{Zone2} ($p = 0.001$), HR_{Zone3} ($p = 0.003$), HR_{Zone4} ($p = 0.001$), HR_{Zone5} ($p = 0.005$), live time ($p < 0.001$), and $SHRZ_{mod}$ ($p < 0.001$). Physiological responses during each quarter, such as heart rate, are dependent upon position played. More time was accumulated in HR_{Zone4}, HR_{Zone5}, for forwards than guards and centers, respectively. Moreover, forwards averaged more live time and had greater $SHRZ_{mod}$ across all 4 quarters when compared to guards and centers. Forwards spend more time in higher heart rate zones when compared to other positions played, which may be due to the higher amount of live time. A main effect of quarters was also noted. Statistically higher accumulated time in HR_{Zone4} and in HR_{Zone5} during the fourth quarter was noted. Fourth quarter physiological demands are higher than previous quarters, respectively. When analyzing games, statistically higher training loads, time in HR_{zone4}, time in HR_{zone5}, were seen in forwards when compared to guards and centers, but forwards achieved a lower HRpeak than these other positions. During an entire game, forwards spend more time at higher heart rates, yet their highest recorded heart rate remains lower than guards and post players.

Ultimately, basketball is a physically demanding sport that involves a high number of movements in all directions that last for short durations. Throughout the course of a basketball game, the amount of time spent in high intensity activity decreases as does blood lactate levels, respectively. Guards will experience a higher physiological and sport specific skill demands than other positions during the same competition. Male basketball players and female players experience different physical and physiological demand during the sport of basketball. Due to fact that basketball requires a high number of movements performed quickly while heart rates remain relatively high, neuromuscular fatigue can occur and must be both monitored and managed throughout the season.

Physical and Physiological Attributes in Starters vs. Non-Starters

Both fitness level and power production have shown to be differentiate upper level from lower-level basketball players, with upper-level players having higher levels of both fitness and power production abilities (Petway et al., 2020). Fatigue monitoring that fails to utilize assessments that lack sensitivity to fatigue or is unable to assess attributes that disseminate between playing levels should be reassessed and altered in a manner that includes fatigue sensitive tests that measure important attributes related to performance. The following section will review the literature about important attributes for a basketball athlete.

Ostojic et al. (2006) described the structural and functional characteristics of elite male basketball players in addition to evaluating physiological and physical differences between positions. Guards were found to be substantially more experienced and older than forwards and centers. Centers had statistically more body fat, higher body mass, and more height, but lower $VO2_{max}$ values than both the guards and forwards. Center is a position played by larger athletes who have a lower level of cardiovascular fitness when compared with guards and forwards. When compared to guards, vertical jump power was statistically higher for centers, but vertical jump height was not statistically different between any position. Centers jump with higher body mass than guards, which in turn will affect power output. Vertical jump height appears to be independent of position played in elite male basketball players. Statistically significant positive correlations were noted between weight and body fat ($r = 0.92$, $p < 0.01$) and height and body fat ($r = 0.85$, $p < 0.01$), whereas statistically significant negative correlations were observed between weight and vertical jump ($r = -0.99$, $p < 0.01$), weight and estimated $VO2_{max}$ ($r = -0.99$, $p < 0.01$), height and vertical jump ($r = -0.98$, $p < 0.01$), and height and estimated $VO2_{max}$ ($r = -0.95$, $p < 0.01$). Significant relationships exist between body size, body weight, vertical jump performance, and cardiovascular fitness levels in elite male basketball athletes. These relationships between body size and jumping performance may be of importance when attempting to identify talent.

Spiteri et al. (2015) assessed the strength components and kinetic profile required for a faster change of direction (COD) and agility performance in female basketball players. The players completed a maximal dynamic strength test, concentric and eccentric strength test, isometric strength test, COD tests, and multi-directional agility test via various laboratory instruments and techniques, respectively. Following completion of performance tests, players were classified into either a slower (lower 50th percentile) or faster group (upper 50th percentile) for COD and agility based on total running time required to complete each test (Spiteri et al., 2015). The faster athletes had statistically faster COD times during the 505 (2.43 ± 0.18 m.s^{-1} vs. 3.03 ± 0.30 m.s^{-1}; $p = 0.01$, ES = 2.42), the lowest total time for the T-test (10.36 ± 0.81 m.s^{-1} vs. 12.75 ± 0.45 m.s^{-1}; $p = 0.01$, ES = 3.64) when compared with the slower athletes. Faster athletes were able to change direction during the 505 and T-test at faster velocities than the slower athletes. During the agility based test, the faster athlete had statistically faster first COD time (0.15 ± 0.03 m.s^{-1} vs. 0.20 ± 0.12 m.s^{-1}; $p = 0.04$, ES = 0.43), total time (4.47 ± 0.62 m.s^{-1}

vs. 5.34 ± 0.25 m.s^{-1}; $p = 0.04$, ES = 1.84), and first directional change time (1.72 ± 0.50 m.s^{-1} vs. 2.36 ± 0.12 m.s^{-1}; $p = 0.03$, ES = 0.57). The faster athletes were able to decide and complete the initial COD movement pattern faster than slower athletes. Faster athletes appear to have superior perceptual cognitive ability than slower athletes when faced with an agility task. The faster athletes had statistically greater vertical braking forces ($p = 0.02$; ES = 1.88) and greater vertical propulsive forces ($p = 0.02$; ES = 1.72) during the 505 COD test when compared with the slower athletes. Faster athletes also had statistically significant within group differences in vertical braking force and vertical propulsive force during both the T-test and agility test, respectively.

This data suggests that faster athletes can produce more relative vertical propulsive force and vertical braking force when compared with slower athletes during a change of direction and an agility task.

When impulse was examined, vertical braking impulse was statistically greater during the agility test for the slower athletes when compared with the faster athletes (REF). Because impulse is the product of time and force, and the faster athletes had statistically significantly shorter ground contact times for the 505 test (0.42 ± 0.03 vs. 0.47 ± 0.04 s), T-test (0.32 ± 0.03 vs. 0.35 ± 0.03 s), and agility test (0.42 ± 0.04 vs. 0.51 ± 0.05 s), the slower athletes generated greater impulse through longer ground contact time while planting during the agility test. This may be due to an inferior perceptual cognitive ability or lower levels of relative isometric strength when compared to faster athletes. In contrast, vertical propulsive impulse was statistically greater for the faster athletes during the T-test and agility test when compared with the slower athletes. Faster athletes generate higher vertical propulsive impulse during a change of direction and agility task than slower athletes. Faster athletes during the agility test had statistically lower body mass ($p = 0.03$) and statistically significantly higher relative lean mass (p

= 0.04) when compared to the slower athletes. For T-test performance, the faster group had statistically lower body fat percentage (22.27 ± 6.80% vs 31.7 ± 6.76%; $p = 0.03$) when compared with the slower group, respectively. Athletes with higher lean body mass and lower total body mass have superior performance during a change direction and agility task when compared to athletes with less lean body mass and higher total body mass. Faster athletes in the 505 COD assessment had statistically greater relative eccentric (1.44 ± 0.20 kg·BW^{-1} vs 1.14 ± 0.22 kg·BW^{-1}; $p = 0.01$; ES = 1.42) strength, as measured by a maximal eccentric only squat (REF). These data suggest that higher levels of relative eccentric strength appear to be important in delineating between fast and slow athletes during change of direction tasks.

For both the 505 COD and T-test, the faster athletes had statistically higher relative isometric strength (1.45 ± 0.37 N·BW^{-1} vs 0.99 ± 0.13 N·BW^{-1}; $p = 0.02$; ES = 0.94) as measured by a maximal isometric mid-thigh pull (REF). For athletes participating in sports requiring change of direction ability, increasing relative eccentric and isometric strength capacities are likely of importance.

Interestingly, while the strength characteristics between faster and slower athletes were substantially different, the percent contribution of each strength measure to both COD and agility performance was very similar. Based on this finding, it is apparent that all strength qualities are used during COD and agility movements. More importantly for female athletes, this study suggests that developing a greater strength profile across all characteristics, instead of redistribution of strength characteristic development, can produce faster COD movement, redistribution of strength quality development.

Athletes with faster change of direction and agility capabilities have lower percent body fat, lower overall body mass, higher relative isometric concentric and eccentric strength abilities in addition to superior perceptual cognitive processing capabilities (Spiteri et al., 2015). Understanding the overall importance of specific physical characteristics is important for coaches during talent identification as well as during preparation periods, however differences in physical attributes that are required to excel exists between positions.

Kucsa and Mačura (2015) analyzed differences in physical characteristics based on playing positions in female basketball players. Players were split into center, forward, and guard position groups and then completed anthropometric tests, ¾ court sprint, shuttle test, lane agility drill, no step vertical jump, maximal effort vertical jump with step, and VO_2 max testing prior to an international level competition. For height and weight, the tallest (186.73 ± 3.20cm) and heaviest (73.05 ± 9.25kg) players on average were the center position players. Guards had the lowest body fat percentage (15.96 ± 2.41%) and highest results for VO_2 max tests (47.73 ± 5.71 $ml \cdot kg^{-1} \cdot min^{-1}$). But no statistically significant differences between playing position were noted for anthropometrics or VO_2 max tests results, which may be due to a low number of subjects or because of the homogeneity of the players in the study. Additionally, no statistically significant differences were found between playing position and running speed, quickness, agility, or vertical jumping power results. When comparing results in the ¾ court sprint test (3.73 ± 0.16s), shuttle test 17.43 ± 0.56s), and power output from both vertical jump tests (47.16 ± 3.06cm, 57.00 ± 3.40cm) the guards had better results on average when compared to forwards or centers. Guards had superior ability to move their body weight during a linear sprint, a repeated linear sprint, and during jumping when compared to taller and heavier athletes. The forwards had the fastest times for the lane agility drill test (12.54 ± 0.43s) when compared to guards and centers, while the centers had a lower average no-step vertical jump (43.00 ± 4.69cm) and maximal vertical jump (53.00 ± 3.86 cm) when compared to the guards and forwards, respectively. Forwards were better able to complete multiple movements in a shorter period of time than guards and centers, whereas surprisingly, centers had lower jumping abilities than guards and forwards (Kucsa & Mačura, 2015). This finding is surprising because taller people, to a point, have higher VJs, as they have a greater acceleration distance (longer legs), thus the centers in this study more than likely lacked relative strength when compared to smaller framed guards and forwards. Although no statistically significant differences were found between playing groups, guards tended to have greater linear speed, repeat linear speed, and power output via no-step and maximal jump effort with steps when compared with other playing positions. Forwards had superior ability to shuffle, backpedal, and change direction when compared to guards and centers; whereas centers were taller, heavier, and had lower jumping abilities than both the guards and the forwards.

Basketball players at higher levels exhibit superior fitness and power production compared to lower-level players, emphasizing the importance of these traits in player differentiation. Monitoring fatigue in basketball should include assessments that are sensitive to fatigue and can measure performance-related attributes. Physical characteristics vary among playing positions, with guards typically having better sprinting abilities and centers possessing larger bodies but lower jumping abilities. Overall, the relationship between body size, physical attributes, and performance highlights the significance of considering these factors preparing players for the demands of basketball.

Physical Changes Across A Season. Hoffman et al. (1991) examined the effects of a division 1 basketball season on strength, speed, and endurance in players. Prior to the start of pre-season (RTP), at 5-weeks into pre-season (PRES), midseason (MS), and after post season tournament, athletes completed anthropometric tests, 1 repetition maximum bench press, squat, 27-meter sprint, T-test, vertical jump with arm swing, 1.5-mile run, and a single leg isokinetic and isometric dynamometer test. A formalized resistance training program took place during the 5-weeks of pre-season. Results showed that following the 5-weeks of resistance training, statistically significant improvements in 1RM squat and single leg isokinetic strength when compared to RTP values. A pre-season resistance training program improved both dynamic and isokinetic lower body strength. Moreover, statistically significant 1RM squat and vertical jump height decreases were noted in addition to a statistically significant increase in 27-m sprint times were noted at midseason when compared with values measured at PRES. Player's dynamic maximal strength, power output ability, and speed were all negatively affected following participation in basketball practice without continuation of a formalized resistance training program (Hoffman, Andrew C. Fry, et al., 1991). Interestingly, at the final testing period (one or two days after end of postseason tournament) the player's isometric and isokinetic strength levels were not substantially affected following the start of basketball practice. Although, no mention of familiarization period with these either the isometric or isokinetic testing protocols was mentioned, which may affect outcome. Participation in basketball practice may elicit adequate stimuli to maintain isokinetic and isometric strength levels in the lower body when compared with RTP values. Isokinetic and isometric strength may be less sensitive to fatigue when compared with dynamic strength, respectively (Hoffman, Andrew C. Fry, et al., 1991). Statistically significant increase in linear sprint times and decreases in 1RM back squat values remained during post-season testing when compared to pre-season and RTP values, but isokinetic strength statistically improved at the post-season timepoint when compared to RTP.

Throughout a basketball season, sprint times, 1RM back squat values, and vertical jump ability were decreased. Upper body, isokinetic and isometric strength remained constant or improves throughout a basketball season. Resistance training was not maintained throughout the season, which may have influenced these results.

Hoffman, Maresh, et al. (1991) examined the efficacy of an in-season resistance training program on specific characteristics in division 1 male basketball players. Players participated in testing sessions that included 1RM bench press, 1RM back squat, 27-m sprint, T-test, and a vertical jump with arm swing prior to the start of official practice and then 48 hours following the end of season. Group 1, considered untrained players, participated in a 5-week pre-season resistance training program, but no in-season resistance training and were considered the control group for this study. Group 2, also considered untrained players, participated in the 5-week preseason resistance training program and in-season resistance training, whereas group 3, who were considered trained, took part in the 5-week preseason and the in-season resistance training protocol. All resistance training protocols followed progressive overload training progressions. The pre-season resistance training program was designed in such a manner that players would attain peak strength levels by the start of official basketball practice (Hoffman, Maresh, et al., 1991). The in-season resistance training program took place twice per week with 48 to 96 hours between each session. Results for group 3 players who also participated in a 6-month offseason resistance training program showed substantially increased body weight, 1RM bench press, and 1RM squat following the off season RTP. A 6-month resistance training protocol during the off-season was effective in increasing maximal upper body and lower body strength levels. Group 2 had statistically significant increases in 1RM bench press strength following the in-season RTP. An in-season training program was effective in improving upper body strength. For group 1, no in-season resistance training, a statistically significant increase in post-season 27-m time when compared to pre-season times. Players that did not participate in resistance training during the in-season period increase sprint times from pre-season to post-season. When examining between group differences, group 2 showed statistically faster 27m sprint time than group 1 at post-season ($p < .05$) and group 3 was statistically stronger in the 1RM bench press than group 1 at pre-season ($p < .05$). Interestingly, no other statistically significant differences were noted between group 1 and group 2.

Players that resistance trained during pre-season and during the in-season period have faster sprint times than players who did not. Players that resistance trained in an off-season RTP, had a higher level of upper body strength than players who were untrained (Hoffman, Maresh, et al., 1991). Additionally, group 3 players were able to maintain all pre-season strength and performance results throughout a full division 1 basketball season. Athletes who were trained prior to the start of a collegiate basketball season were able to maintain strength and performance measures throughout the season more so than their untrained teammates.

Several researchers have investigated the effects of a division 1 basketball season on player performance (Edwards et al., 2018; A. Heishman et al., 2020; A. D. Heishman et al., 2018; Hoffman, Andrew C. Fry, et al., 1991; Hoffman, Fry, et al., 1991; Ransdell et al., 2020; Stojanović et al., 2018; Towner et al., 2023). A formalized resistance training program during the pre-season resulted in significant improvements in lower body strength and power. However, without continued resistance training during the season, players experienced decreases in squat strength, vertical jump ability, and sprint times. Notably, isometric strength levels were unaffected by basketball practice, indicating a potential resilience to fatigue compared to dynamic strength. These results indicate that engaging in in-season resistance training and prioritizing resistance training during the off season can result in increased upper body strength, faster sprint times, and improved ability to maintain a higher level of performance throughout the season.

Monitoring Practices Used in Sport

Less fatigable athletes typically have higher workload capacities, thus can withstand more work before becoming fatigued (Edwards et al., 2018; Enoka & Duchateau, 2017). During a long season, accumulation of fatigue can affect the on court performance of a basketball player and incorporating multiple fatigue monitoring tools could provide coaches with information concerning how athletes are or are not responding to training and competition stressors (Edwards et al., 2018). The fatigue monitoring tools can include inertial measurement units, countermovement jumps performed on force plates, and blood biomarkers. An IMU can provide a range of data that quantifies movement demands (number of accelerations/decelerations, position, velocity, direction) involved with basketball during training and competition (Edwards et al., 2018; J. J. Malone et al., 2017). IMUs are able to be used on an individualized basis and due to differences in physical and physiological demands during basketball, coaches now have the ability when given the time and resources to individualize drills during training (Edwards et al., 2018; Schelling & Torres, 2016). Specifically, Catapult Optimeye monitors, sampled at 100 Hz, have previously been used and shown to be reliable in female and male basketball players to objectify external workloads via PlayerLoad and IMA (A. Heishman et al., 2020; Montgomery et al., 2010; Peterson & Quiggle, 2017). The monitors are worn posteriorly on the thoracic region between the shoulder blades of each player inside a special harness garment. PlayerLoad is an estimate of accumulated physical demand and is expressed in arbitrary units (Montgomery et al., 2010; Peterson & Quiggle, 2017). A variety of sports have recorded different PlayerLoad values during competitions and training sessions, therefore sport specific monitoring of PlayerLoad is recommended when comparing and planning workloads (C. D. Gómez-Carmona et al., 2020; Mooney et al., 2013; Read et al., 2017; Trewin et al., 2018). This metric is calculated by taking the instantaneous rate of change in acceleration in the anteroposterior, mediolateral, and vertical planes and multiplying the resultant value by 0.01 to reduce value to a manageable number (Montgomery et al., 2010; Peterson & Quiggle, 2017). PlayerLoad per minute utilizes the same formula as PlayerLoad but uses total duration of the session to generate a value. When discussing IMA, this metric uses raw accelerometer and gyroscope data to detect and quantify the frequency of sport specific movements within a variety of intensity thresholds. IMA is expressed as count data and is quantified during post session processing via the application of polynomial smoothing curves between the start and end point of identified accelerative events (A. Heishman et al., 2020; Montgomery et al., 2010; Peterson & Quiggle, 2017). The magnitude of each movement is based on the summation of antero-posterior and medio-lateral accelerations that occur over time and is measured in terms of delta-velocity as a unit of impulse, $m \cdot s^{-1}$ (Holme, 2015; Montgomery et al., 2010; Peterson & Quiggle, 2017). Explosive efforts is a high-threshold IMA, which only takes into account anterior-posterior and medio-lateral accelerations ≥ 3.5 m/s and vertical accelerations that are ≥ 25.4 cm, respectively (Holme, 2015; Peterson & Quiggle, 2017). These devices have been established as effective means for quantifying these events in indoor activities (Boyd et al., 2011; Holme, 2015; Montgomery et al., 2010; Peterson & Quiggle, 2017).

When using force plates to monitor fatigue via the analysis of specific force time characteristics during a countermovement jump, the use of jump height (JH), modified reactive strength index (RSI_{mod}), and average braking rate of force development (ECC-RFD) have been previously used with athletes (R. Gathercole et al., 2015; R. J. Gathercole et al., 2015; A. Heishman et al., 2020; A. D. Heishman et al., 2018; Laffaye & Wagner, 2013). The calculation of jump height from flight time has been shown to be similar to net-impulse-derived jump height because both reflect the vertical flight of the centre of mass (Kibele, 1998; Mizuguchi et al., 2015). In addition, reliability of jump height calculated from flight time has been shown to be acceptable (Mizuguchi et al., 2015; Moir et al., 2009; Slinde et al., 2008). Modified reactive strength index (RSI_{mod}) is is a measure of lower body explosiveness (Beckham et al., 2014; Ebben & Petushek, 2010a; Kipp et al., 2016a; Suchomel, Bailey, et al., 2015a; Suchomel et al., 2016). RSI_{mod} has been shown to be reliable across a variety of division 1 team sport athletes (Suchomel, Bailey, et al., 2015a). In addition to being a reliable metric derived from both unloaded and loaded CMJs performed on force plates, RSI_{mod} has been shown to not only differ between positions and sports but also change with increases in external workloads (A. Heishman et al., 2020; Suchomel, Bailey, et al., 2015a). RSI_{mod} is calculated as, jump height divided by time to take off and is represented in the unit of $m \cdot s^{-1}$ (A. Heishman et al., 2020; Suchomel, Bailey, et al., 2015a). Lastly, average braking rate of force development has been used to monitor jumping performance (R. Gathercole et al., 2015; R. J. Gathercole et al., 2015b; Laffaye & Wagner, 2013). Because rate of force development plays a critical role in activities such as sprinting and jumping, the ability for an athlete to maintain or improve this metric is important. Specifically examining the eccentric phase of a CMJ may provide novel insight to neuromuscular fatigue as a decrease in muscle reflex sensitivity occurs to minimize further damage to the muscle fibers, respectively (Avela et al., 1999; R. Gathercole et al., 2015). Average ECC-RFD (N x s^{-1}) can be calculated from the slope of the line when force exceeds body weight and ends when velocity reaches zero or at the bottom of the descent when loading for the CMJ, respectively (Laffaye et al., 2014). Time to take-off was calculated as the time when the athlete's bodyweight crosses below 98% of an established steady weight mark to the point of take-off from the force plate (Laffaye et al. 2014). The steady weight mark is based on finding a 0.7s segment where the RMS of point-to-point deltas is below 0.3 N (personal communication with Sparta Science Data Engineer). The following section will detail multiple studies that examined workloads and multiple studies that examined CMJs.

An athlete's inability to produce and sustain power output levels can significantly impact sport performance across the entire basketball season. To monitor fatigue levels, coaches can use various tools such as inertial measurement units (IMUs), countermovement jumps (CMJs) on force plates, and blood biomarkers. Assessing fatigue through the analysis of force-time characteristics during CMJs, such as jump height, modified reactive strength index (RSImod), and average braking rate of force development (ECC-RFD) may offer insight into lower body explosiveness, neuromuscular fatigue, and jumping performance. Practitioners can gain valuable information and adjust training and workload totals when these monitoring tools are appropriately used.

Workload

External workload can be defined as the mechanical and locomotor actions performed by an athlete and measured via speed, power, impacts, changes of speed and direction (Buchheit et al., 2018; C. D. Gómez-Carmona et al., 2020). Inertial measurement units (IMUs) can be used by high level sports performance teams in an effort to measure athletes' external workloads during training and competitions (Atkinson & Nevill, 1998; Bland & Altman, n.d.; C. D. Gómez-Carmona et al., 2020; Sands et al., 2017). This wearable technology has been previously used in basketball (Bastida-Castillo et al., 2019; Fox et al., 2017; C. D. Gómez-Carmona et al., 2020; Peterson & Quiggle, 2017; Pino-Ortega et al., 2019; Schelling & Torres-Ronda, 2016). IMUs and can be considered reliable and an acceptable alternative to the gold standard, video analysis, when used for player tracking and quantification of external workloads (Atkinson & Nevill, 1998; Bastida-Castillo et al., 2019; Bland & Altman, n.d.; C. D. Gómez-Carmona et al., 2020; Peterson & Quiggle, 2017; Sands et al., 2017). It is recommended that a sampling frequency of 100Hz is suitable to detect external workloads in invasion team sports (C. D. Gómez-Carmona et al., 2020). Specifically, the use of a tri-axial accelerometer provides analysis of acceleration in the medio-lateral (y), anterior-posterior (x), and vertical axes (z), all of which occur in sporting environments (Boyd et al., 2011; C. D. Gómez-Carmona et al., 2020; Peterson & Quiggle, 2017). Technical features of accelerometers used should be described within each study. Certain models of devices are unable to identify peak force generation because of limited output ranges and will impact the accuracy in detecting movements during training and competitions, respectively (C. D. Gómez-Carmona et al., 2020). The within and between device reliability and convergent validity has been demonstrated in MinimaxX (Catapult Sports) accelerometer devices (Barrett et al., 2014; Boyd et al., 2011). Gómez-Carmona et al. (2020) conducted a systematic review examining recommendations regarding the use of accelerometry to measure and monitor workload in invasion team sports. It was noted that less than a third of studies that met the authors inclusion criteria reported accelerometer data from training and even less included elite female athletes (13%), which highlights the need for accelerometer data from training sessions that include elite female athletes. Additionally, differences in measured workloads during competition and training have been noted in various invasion team sports (Chandler et al., 2014; Fox et al., 2018; Gentles et al., 2018; C. Gómez-Carmona et al., 2018; Ritchie et al., 2016; Young et al., 2016). The following pages include studies that have quantified external workload.

Svilar and Jukić (2018) sought to establish a relationship amongst external training load variables (ETL) and establish a relationship between external and internal training (ITL) loads of male basketball players. ITL was monitored via session RPE (sRPE) and ETL was monitored with S5 devices that house an accelerometer, gyroscope, and a magnetometer sensor. These devices collected multiple metrics that the authors used for correlations. Players were monitored specifically during the in-season period and during basketball only training which included practice and multiple competitions per week, respectively. Results indicated that PlayerLoad in the vertical plane (206.1 ± 59.9 AU) and deceleration demands (89.1 ± 32.2 n) were higher in accumulation when compared to PlayerLoad values in the anterior/posterior (132 ± 37.3 AU), lateral plane (127.4 ± 37.4 AU) and acceleration demands (49.1 ± 24.2 n). During an in-season phase, elite level male basketball players will experience higher loads in the vertical plane and complete more decelerations than accelerations, which may be a result of the high percentage of running activity and decelerations that have been recorded during basketball competitions (Koyama et al., 2022; Svilar & Jukić, 2018). Statistically significant relationships between PlayerLoad and all examined external training load variables within PlayerLoad were noted. The highest correlations were between PlayerLoad and total change of direction (r = 0.84; CI = 0.80-0.87) and total decelerations (r = 0.83; CI = 0.79-0.86). These relatively high correlations may exist because PlayerLoad includes movements from all three planes and because decelerations have a higher frequency during basketball when compared to frequency of accelerations (Koyama et al., 2022; Svilar & Jukić, 2018). Additionally, external training load variables within

PlayerLoad were classified into total variables and high-band variables. Aside from the jump variable, the high-band variables had lower correlations with PlayerLoad than total variables, though this could be due to the higher occurrence of total variables when compared to the occurrence of high band variables within PlayerLoad during basketball. Statistically significant correlations were found between sRPE and all chosen external training load variables ($p <.01$). Correlations between sRPE and PlayerLoad, PlayerLoad in anterior/posterior plane, PlayerLoad in lateral plane, and PlayerLoad in the vertical plane all had r values above 0.8. Session RPE appears to be an appropriate method to quantify perception of training intensity when compared with the objective PlayerLoad variable. Worth noting, once again the total count of decelerations, change of direction, and accelerations had higher correlations with internal training load than high-band category of the same variables. Total counts of basketball specific movements illicit a higher internal training load response than exclusively examining these same movements in high-band thresholds. This information may be important for sport performance coaches. Workload and imposed physical demand will change based on the format of a training drill or tactical strategy during a competition. In order for coaches to optimally prepare athletes for the demands of basketball, understanding the external workloads of various formats of training drills is important.

Schelling and Torres (2016) aimed to quantify workload using accelerometers in male professional basketball players during specific training drills. Data was collected from an accelerometer worn between the player's hip and belly on the right iliac crest during training sessions. Training sessions were recorded from an in-season period over the course of 4 weeks for a total of 1139 training observations and included 95 ± 33 training drills. These training drills were designed by sport coaches and were intended to improve skill, tactical, and physical capacities of players. Each drill was classified based on number of players involved and the court size used to execute the drill. Results indicated that in full court drills, a higher acceleration load per minute occurred during 3v3 (18.7 ± 4.1 AL/min) and 5v5 (17.9 ± 4.6 AL/min) scrimmage drills, but were lowest during 4v4 (13.8 ± 2.5 AL/min) (Schelling & Torres, 2016). Full court 3v3 and 5v5 drills impose a higher level of intensity on players than full court 4v4. For half court drills, highest acceleration load per minute occurred during 2v2 (12.7 ± 2.7 AL/min) and 5v5 (12.0 ± 5.6 AL/min) and the lowest load per minute occurred during 4v4 (10.8 ± 2.3 AL/min). In the half court, 2v2 and 5v5 drills impose the highest level of intensity on players. When examining differences in accelerometer load between number of players involved in a full court drill, small and moderate differences, most likely with lower values, were noted when comparing 2v2 to 3v3 and 5v5, and 4v4 to 5v5. In the full court, accelerometer load per minute may be dependent upon the number of players involved in a drill. In contrast, the differences in accelerometer load per minute for half court drills showed trivial to moderate differences with a likely increase of 10-20% when comparing 2v2 to all other drill formations. Accelerometer loads in half court drills are higher during 2v2, but this increase may not be of practical significance, respectively.

The number of players involved in a drill and the formation of that drill, impacts the amount of external workload experienced by basketball players. Specifically, full court 3v3 and 5v5 bring about the highest amounts external workloads as measured by an accelerometer load per minute metric. As noted above, workloads differ based on the format of a drill, but workload will also differ based on the intent of the drill or session, respectively.

Fox et al. (2018) sought to describe and compare the differences in external demands and internal responses in semiprofessional male basketball players between physical conditioning training sessions (PCT), games-based training (BGT), and competition (Comp) across various seasonal phases. When comparing external demands as measured by triaxial accelerometers, a statistically significant difference in absolute playerload (PCT: 632 ± 139 vs. BGT: 624 ± 113 vs. Comp: 449 ± 118 AU; $p < .001$) and relative playerload (PCT: 6.50 ± 0.81 vs. BGT: 6.10 ± 0.77 vs. Comp: 4.35 ± 1.09 $\mathrm{AU{\cdot}min^{-1}}$; $p < .001$) was observed when PCT and BGT were compared with the competition phase, respectively. After post-hoc testing, PCT and GBT produced statistically higher absolute and relative PL when compared with competition. During the PCT phase and the GBT phase of the season, players experience a higher absolute and relative workload than during the competition phase of the season. These higher external workloads may be the result of longer duration training sessions when compared with duration of competitions and overall, less total rest periods during PCT and GBT, respectively. Session rating of perceived exertion (sRPE) was also examined during each phase of the season and a statistically significant difference between PCT (6.00 ± 1.12 $\mathrm{AU{\cdot}min^{-1}}$) and GBT (5.00 ± 1.32 $\mathrm{AU{\cdot}min^{-1}}$) was observed. Physical conditioning training session appears to induce a higher subjective load response than a GBT approach, which may be due to the inclusion of basketball specific tactical and technical drills during games-based training. Moreover, although PCT and GBT generated statistically higher objective external workloads than competition, perceived relative exertion from the players was lowest during GBT and not during competition. Competition dependent stressors may influence a player's perception of exertion. Lastly, a sRPE:PL ratio, a direct comparison of a player's response to imposed stimulus, was calculated and a statistically higher competition sRPE:PL ratio was noted when compared to PCT and GBT sRPE:PL ratios. Once again, competition appears to induce exclusive stressors on basketball players when compared to stressors of either physical training or games-based training sessions (Fox et al., 2018).

Physical training, games-based training, and competition phases throughout a seasonal period induce phase specific external and internal demands and responses from semiprofessional male basketball players. Competition phase provokes higher levels of perceived exertion when compared to games-based training and physical conditioning training, which may help coaches better periodize phase specific training during a season. When planning training throughout the season, coaches must know the demands being placed on all players of the team, regardless of starting status.

Fields et al. (2021) investigated differences in games and practice external training loads during in-season play between starters and non-starters. Division 1 male soccer players' external training loads, which included total distance covered, player load, high speed distance, high inertial movement analysis (IMA), and repeated high intensity efforts, were monitored via GPS technology during a total of 11 sessions that included 3 games. Results indicated that total distance, player load, high-speed distance, IMAs, and repeated high intensity efforts were statistically different between starters and non-starters ($p<0.001$). Additionally, starters experience higher levels of physical stress in Division 1 soccer when compared to non-starters. Overall, starters experienced lower external load measures in all measured practices but one (practice 3), when compared to games ($p<0.001$). Specifically, total distance covered (2922 ± 1234 vs 8064 ± 3133 m), player load (369 ± 132 vs 923 ± 279 AU), high-speed distance (63 ± 54 vs 287 ± 162 m), IMAs (15 ± 9 vs 34 ± 16 m), and repeated high intensity efforts (8 ± 5 vs 23 ± 10 #) were all statistically lower in training than in games for starters. Games provide higher levels of physical stress when compared to practice sessions for starters in soccer. Statistically lower practice loads were experienced by non-starters when compared to game loads of the starters ($p<0.001$). Non-starters experience less load in practice sessions than starters experience in games and may require additional physical training. Interestingly, for the external workload measures of high-speed distance or IMAs during practice, no statistically significant differences were noted between starters and non-starters. Starters experience lower distances of high-speed running and a lower number of explosive efforts during practice, which may indicate a conservation of energy strategy prior to games possibly due to being withheld from completing an entire practice.

These results suggest that starters undergo higher levels of external workloads during games than during practices and non-starters do not experience the same level of external workloads during practice sessions that starters experience during games. Special attention to the amount and type of recovery that starters undergo between practices and games may be of importance to coaches because of the clear differences in physical stress experienced by starters when compared to non-starters. Adding additional training load to non-starters may be of importance as well, due to the low external workloads experience by non-starters in practice when compared to starter workloads during games. Moreover, the importance of not only understanding the decrements in physical ability due to changes in workload, but also understanding the changes in well-being caused by workloads is important for coaches.

Conte et al. (2021) compared and quantified the well-being and workload values of male basketball players across games played on consecutive days during the in-season phase. External workload was measured via microsensors worn between the scapula of the players, objective internal workload was measured via chest worn heart rate monitors, and subjective internal workload was assessed using session RPE. For well-being measurements, players completed a questionnaire every gameday morning and the sum of all five questions was used to calculate a total well-being score. Results indicated a statistically higher total time (*P* <0.001; ES = large) for games on day 2 when compared to day 1; however, no statistically significant differences in workload were found between games. Workload measurements during basketball games may or may not be affected by the total time of that game (Conte et al., 2021). Additionally, a statistically lower playerload per minute (*P* = 0.03; ES = small) was observed in games on day 2 when compared to day 1. Lower player load per minute during game 2 may be attributed to the greater total time experienced. A statistically lower total well-being score (*P* <0.001; ES = small) was noted on day 2 when compared to day 1. *On* day 2, higher levels of fatigue were apparent when compared to day 1 (*P* <0.001; ES trivial to small), but no other statistically significant differences were found for any other well-being metrics. The second day of two consecutive basketball games is accompanied by lower objective levels of total well-being, with fatigue levels affecting well-being the most. Levels of fatigue increase and total well-being scores decrease on day 2 of consecutive basketball competitions, which may help coaches plan training and recovery prior to and after periods where consecutive competitions occur (i.e tournaments). Unfortunately, the previously mentioned studies examined male athletes and although male and female basketball players play the same sport, the format and physiological demands of the sport are different (Fox et al., 2018; A. T. Scanlan et al., 2012). Because of these noted differences, it is important to quantify workloads experienced by female basketball players.

Paulauskas et al. (2019) sought to quantify fluctuations in weekly workloads while also identifying differences in workload according to playing time in elite female basketball players. Players' workloads were monitored throughout the 24-week in-season phase that included 1-3 weekly competitions, 4-6 weekly training sessions lasting 90 – 120 minutes of basketball specific and strength and conditioning sessions, respectively. Workloads were quantified by the use of sRPE and total weekly training load (TL), weekly TL, weekly game load (GL), acute:chronic workload ratio (ACWR), chronic workload, training monotony, and training strain were used as variables for analysis. Results indicated that in week 13 increases in total weekly TL and weekly TL were 47% and 120%, respectively. Along with the increases in total and weekly TL, the ACWR had the highest weekly change (49%) in week 13 as well. Increases in training loads also increase ACWR. Week 13 was the only week of the season with no competitions, therefore the large increases in training loads were the sport coach's attempt to compensate load wise (Paulauskas et al., 2019). As for training monotony and training strain, the highest changes were noted in week 17 (34%) and week 15 (59%), which were both affected by training loads. When players were grouped into high playing time group (942 ± 103 min) and low playing time group (629 ± 123 min), a statistically significant difference was found for quantified game load. When examining total weekly TL, weekly TL, chronic load, ACWR, monotony, and strain, there were no statistically significant differences found between low and high minute players, respectively. Training load of competitions are increased in players who play a higher number of minutes, but other monitoring training load variables are unaffected by playing time, therefore performance coaches must be mindful when adding additional load onto high minute players during in season periods.

Worth noting is that not all IMU devices and software use the exact same technology or hardware, thus comparison between brands may be limited. However, external workload in basketball can be measured using inertial measurement units (IMUs), which measure the intensity and amount of athlete's motion and orientation of that motion. IMUs are a reliable and acceptable alternative to video analysis for measuring external workloads (Edwards et al., 2018;

A. Heishman et al., 2020; Holme, 2015; Peterson & Quiggle, 2017; Ransdell et al., 2020b; Schelling & Torres, 2016; Towner et al., 2023). Different training drills and game formats in basketball can result in variations in external workload. Workloads differ significantly between starters and non-starters and are dependent upon time-points during a season. The plethora of evidence highlights the importance of monitoring external workloads while taking into consideration an individual player's role and phases of the season.

Countermovement Jump

Reliability

A. D. Heishman et al. (2020) sought to establish both intra (within) and inter (between)-session reliability of CMJ performance during a CMJ with arm swing (CMJ AS) and a CMJ without arm swing (CMJ NAS). Division 1 male and female basketball players performed a CMJ AS and a CMJ NAS on separate occasions during the off-season. Training loads prior to testing sessions were controlled and a standardized warm-up was completed prior to each testing session. Results for intrasession reliability of typical CMJ AS and CMJ NAS were relatively similar. Coefficient of variations ranged between 1.6% (Flight time (ms)) to 12.5% (Flight time:Contraction time) for CMJ AS, whereas CV% for CMJ NAS ranged from 1.9 to 8.3%. Coefficient of variation across a wide spectrum of CMJ performance variables is lower in CMJ NAS when compared to CMJ AS. Specifically, the intrasession CV for jump height from flight time was recorded as 3.3% for CMJ AS and as 3.8% for CMJ NAS. CMJ with arm swing is a more natural jump method for basketball players and this may increase consistency when jump height is the metric of choice. These data provide evidence that high performance coaches can assess typical CMJ measures with either a CMJ AS or a CMJ NAS in trained basketball players with confidence that between testing session data is reliable. Intersession reliability results were similar to the previously mentioned intrasession reliability results. Coefficient of variations ranged between 2.6 (Flight time (ms)) to 16.2% (Flight time:Contraction time) for CMJ AS, whereas CV% for CMJ NAS ranged from 2.4 to 9.3%. The addition of arm swing influences the between trial reliability of FT:CT by slightly increasing the CV when compared to CMJ NAS. This may indicate that FT:CT is more reliable when used weekly as a measure of change in performance. Reliability and effectiveness of CMJs to detect neuromuscular fatigue may be impacted by the time point of testing in relation to the training session performed.

R. Gathercole, Sporer, Stellingwerff, et al. (2015) examined the reliability and magnitude of change in CMJ performance to assess neuromuscular function following fatigue inducing activity in collegiate athletes. The CMJ metrics were divided into either typical CMJ metrics (CMJ-TYP) or alternative CMJ metrics (CMJ-ALT). During day s1 to 5 of the study, the intraday and interday reliability of CMJ metrics was examined and from days 6 to 9, the level of sensitivity to fatigue induced changes in neuromuscular function were examined. The fatiguing protocol consisted of the completion of the Yo-Yo intermittent recovery level 2 test (Yo-Yo IR2), a five-minute break and then the completion of another Yo-Yo IR2. At the completion of the second Yo-Yo IR2, a five-minute break was given and then the Yo-Yo Intermittent endurance level 2 test was completed, respectively. The assessments following the fatigue inducing protocol were a 20-m sprint and CMJ tests. For data analysis, the four most consistent CMJ attempts were used based on individual scores of mean eccentric and concentric power over time (MEccConP) (R. Gathercole et al., 2015). Results indicated that CMJ-TYP and CMJ-ALT displayed similar intraday and interday CVs and that comparisons of intraday reliability between days 1, 2, and 3 showed trivial effect sizes. When examining CMJ metric’s ability to detect NM fatigue, a marked difference between time points for force at zero velocity was noted. The highest value of force at zero velocity occurred at baseline (24.4 ± 5.0 N) and the lowest at 0 hours post fatigue inducing protocol (21.7 ± 3.3 N). Force at zero velocity during a CMJ will be negatively impacted immediately following exercise when compared to 24 or 72 hours following exercise (R. Gathercole et al., 2015). Furthermore, peak power (PP) showed reductions at 0 and 24 hours post exercise, while jump duration increased at the same time points. At the 72-hour point, PP returned to baseline values, but jump duration remained extended. Jump duration may be more sensitive to NM fatigue when compared to peak power. MEccConP, defined as the power produced during both eccentric and concentric CMJ phases divided by total duration, was the only metric that displayed a small change at 24 hours post exercise, whereas all other metrics examined displayed only trivial changes at the same time point. The MEccConP variable considers both the eccentric and concentric phase during a CMJ while accounting for time. The inclusion of time and both phases may improve detection of NM fatigue when compared to variables that do not include such measurements. Worth noting is the fact that total impulse and minimum velocity improved at 72h when compared with baseline values, respectively. The authors note that while these metrics appeared enhanced, the CMJs took longer to perform which could indicate NM fatigue.

Overall, decreases in CMJ performance were obvious at 0 hours post exercise. At 24 hours post exercise, a trend towards baseline values did occur, but was then followed by a decrease at 72 h. This timeline can be explained due to multiple factors such as metabolic disruption, inability for optimal excitation-contraction coupling, and a reduction in muscle stiffness (Avela et al., 1999; R. Gathercole et al., 2015; Nicol et al., 2006). Additionally, utilizing CMJ metrics that include time-related variables is of importance. Specifically in this study, FT decreased by only 0.7% but FT:CT decreased by 7.7%, which indicates an alternative movement pattern utilizing longer total jump duration was utilized when compared to baseline. Performance coaches can benefit from including a variety of CMJ measurements that examine not only time-related variables but eccentric related movement patterns of a CMJ. Not only does time at which CMJ testing occur affect sensitivity to detect changes in neuromuscular function, but the intent of the training session can also affect the reliability of the CMJ.

Buchheit et al. (2018) investigated the reliability of running specific measures of neuromuscular function following various conditioning sessions in elite soccer players. Three conditioning sessions that aim to prioritize different physical capacities, strength, endurance, and speed, were completed approximately 3 days post competition. Prior to and following the completion of these conditioning sessions, countermovement jump, and adductor squeeze strength were assessed. Additionally, running activity, heart rate, and RPE were being recorded during and after each session, respectively.

Results indicated small typical errors for CMJ height (0.44) and groin strength measures (0.22) as well as very high ICCs for CMJ height (0.83) and groin strength measures (0.96). CMJ height and adductor squeeze strength measures appear to be reliable measures when assessed between training sessions. During endurance training sessions, total distance and average running pace were very largely and almost certainly greater for endurance compared with strength or speed conditioning sessions and time spent above 90% of maximal HR was slightly greater for the endurance session as well. When looking at distance at high speed and peak velocity, these two variables were very largely and almost certainly greater for speed. Priority of a conditioning session will dictate total distance covered, percentage of heart rate athletes will work at, and total distances covered at high speeds (Buchheit et al., 2018). For adductor squeeze strength, possible-to-very likely small decreases were noted from pre- to post strength (-12%), endurance (-7%), and speed (-7%) conditioning sessions. The ability to maintain adductor squeeze strength is negatively impacted independent of conditioning session priority. Countermovement jump height had a small increase following speed (+6%, likely) and endurance (+5%, possibly) conditioning sessions, but changed following strength session were unclear (-2%). An athlete's ability to produce force via countermovement jump, may be enhanced following a speed and endurance conditioning session, but not following a strength conditioning session. The strength conditioning session was described as the session with the highest level of neuromuscular demand, which has been shown previously to negative impact power production in athletes (Cormack et al., 2008).

The priority of a conditioning session does not impact the reliability of CMJ height measures and groin strength measures, but a players ability to produce force and maintain adductor strength are influenced by the priority of a conditioning session, respectively (Buchheit et al., 2018). Understanding the physiological impacts following conditioning sessions that focus on different physical aims, may help coaches periodize conditioning sessions more effectively.

Multiple investigations have examined the reliability and sensitivity of jump performance and neuromuscular measures in athletes. The findings suggest that coaches can use various jump metrics to monitor athletes' performance and detect neuromuscular fatigue, while considering the influence of training sessions on these measures. Understanding the physiological impacts of conditioning sessions targeting different physical aims can help coaches optimize training programs.

Impact of Protocol on Countermovement Jump Metrics

A. Heishman, Brown, et al., (2019) and colleagues examined differences in selected CMJ metrics with the use of arm swing versus no arm swing in addition to examining possible relationships between the selected CMJ metrics. Division 1 male and female basketball players performed CMJ with arm swing (CMJ AS) and without arm swing (CMJ NAS) during an off-season period. The following were assessed, $\text{RSI}_{\text{Mod}}^{\text{FT}}$, $\text{RSI}_{\text{Mod}}^{\text{IMP}}$, and FT:CT. $\text{RSI}_{\text{Mod}}^{\text{FT}}$, $\text{Jump}^{\text{HeightFlightTime}}$ /Contraction Time, was calculated using jump height from flight time (Jump $\text{Height}^{\text{FT}} = \frac{1}{2}\, g(t/2)^2$). $\text{RSI}_{\text{Mod}}^{\text{IMP}}$, Jump $\text{Height}^{\text{Impulse}}$/Contraction Time, was calculated using jump height from impulse-momentum method (Jump $\text{Height}^{\text{IMP}} = v^2/2g$). Furthermore, FT:CT was calculated as flight time divided by contraction time (A. Heishman et al., 2019). Results indicated that CMJ with arm swing had statistically higher $\text{RSI}_{\text{Mod}}^{\text{FT}}$ ($d = 0.67$; $p < 0.001$), $\text{RSI}_{\text{Mod}}^{\text{IMP}}$ ($d = 0.66$; $p < 0.001$), and FT:CT ($d = 0.562$; $p < 0.001$) when compared with CMJ NAS. CMJ with arm swing increases flight time and reduces contraction time when compared to CMJ NAS. When examining the relationship between both $\text{RSI}_{\text{Mod}}^{\text{FT}}$ and $\text{RSI}_{\text{Mod}}^{\text{IMP}}$, statistically significant correlations were noted regardless of type of CMJ or testing session ($r = 0.878$ – 0.986, $p < 0.001$). This strong relationship between both RSI_{Mod} is to be expected due to similarities in each equation. When examining the relationship between FT:CT and both RSI_{Mod} values, a statistically significant positive correlation was seen with CMJ AS and CMJ NAS ($r = 0.864$ – 0.969, $p < 0.001$), respectively. Independent of countermovement jump protocol and method used to calculate jump height, strong relationships exists between FT:CT and RSI_{Mod}. When using flight time to calculate RSI_{Mod}, values ranged from -0.038 less to 0.054 greater than when impulse momentum method was used during the CMJ NAS, however with CMJ AS values ranged from -0.265 less and 0.209 greater than when impulse momentum method was used. The method used to calculate jump height in conjunction with countermovement jump protocol will affect the calculated RSI_{Mod}.

The protocol used during countermovement jump testing does affect measured outcome variables. Arm swing may be more appropriate in highly training jumping athletes and to measure long-term performance outcomes, while CMJ NAS may be more appropriately used on a more frequent basis to monitor acute changes in athletes. High performance coaches must be aware of how protocol and formulas used affect the CMJ metric being used in the decision-making process. Also worth noting is that coaches can utilize either RSI_{Mod} or FT:CT to monitor neuromuscular changes in athletes as they provide similar information about an athlete's force-time characteristics (A. Heishman et al., 2019).

Delextrat et al. (2012) investigated changes over the course of one week during the competitive season in strength, sprint and jump performance in elite female basketball players. Assessments were taken ~6 weeks after the start of the competitive season (mid-November). The selected week for the study was said to be representative of a typical week and included four 120-min practice sessions and one competitive game (four 10-min quarters) that occurred on the final day of the week. Each player took part in a testing session that consisted of isokinetic testing, countermovement jump, and a 20-m sprint immediately before and immediately after a practice or game. Additionally, session RPE and fluid loss was measured post practice and game. Results indicated that there was a statistically significant effect of practice and game on peak torque of the hamstrings (PTH), hamstrings to quadriceps ratio (H:Q), jump height from a CMJ, and 20-m sprint, respectively. Statistical decreases in post vs pretest values ($P<0.01$) for peak torque of the hamstrings was noted on day 2 (pre: 74.3 vs. post: 66.1 N·m), day 5 (79.4 vs. 70.9 N·m), and day 6 (game-pre: 77.8 vs. post: 71.6 N·m). Hamstring peak torque decreases following basketball practice sessions and a game. However, on day 3, hamstring peak torque value was statistically significantly higher post practice when compared to pre practice values (pre: 69.4 vs.

post 76 N·m). Hamstrings to quadriceps ratio statistically significantly decreased (P<0.01) on days 5 and 6, which reflects the statistically significant decrease in hamstring peak torque on days 5 and 6, respectively. For CMJ performances, statistically significant decreases in jump height were noted on day 2 (pre: 34.2 vs. post: 29.9 cm), day 3 (pre: 33.1 vs. post: 26.6 cm), and day 6 (game-pre: 33.8 vs. post: 29.2 cm). A player's ability to produce power is negatively affected by practice and competition (Delextrat et al., 2012). Interestingly, highest jump height was recorded pre practice on day 1 of the week (35.1 cm), which may indicate a sustained level of neuromuscular fatigue following the first practice session of the week. Statistically significant differences in pre to post 20-m sprint time was seen on day 6 (pre: 3.85 vs. post: 4.13s), which was game day. A basketball player's ability to sprint appears to be maintained following practice, but not following a competition. Also, although the increases in sprint time were not statistically significant, these increases may be meaningful in basketball where speed is important. When comparing pre-test values across the week, statistical decreases between day 3 pre-test and baseline (day 1) values for peak torque of the hamstring (day 1: 77.5 vs. day 3: 69.4 N·m) and CMJ height (day 1: 35.2 vs. day 3: 33.1 cm) were noted. These significant decreases in performance may indicate that players experience a substantial amount of fatigue following 3 consecutive practice sessions (Delextrat et al., 2012). When examining training load calculated via session RPE, a statistically significant correlation between change in PTH and training load was found on day 3 (r = -0.691) and day 6 (r = -0.602). On day 3, post-practice PTH values were higher than pre-practice values in addition to the lowest daily recorded training load occurring on day 3, respectively. A lower training load during practice may result in less fatigue of the hamstrings. On day 5, a statistically significant correlation between training load and change in H:Q (r = -0.675) and change in CMJ jump height (r = -0.599). Higher training loads and competition negatively impact a player's hamstring to quadriceps peak torque ratio as well as a player's ability to produce force via CMJ. Following higher training loads, players may benefit from extra recovery efforts. Specifically on game day, statistically significant correlations were found between playing time and changes in PTH (r = -0.603) and changes in 20m time (r = 0.705), respectively. Playing more minutes during a game will negatively impact a players ability to produce a muscular contraction and sprint when compared to playing less minutes during a game (Delextrat et al., 2012). Lastly, statistically significant correlations between frequency of jumps and change in CMJ performance (r =-0.633), sprint frequency and changes in 20-m sprint time (r = 0.705), run frequency and changes in 20-m sprint time (r = 0.601), and between high-intensity shuffle frequency and changes in H:Q (r = -0.756) were observed as determined by video recordings during competition on day 6. These results suggest that higher frequency of movements during a competition, impair a player's ability to produce force vertically or horizontally. Neuromuscular performance is altered by practice sessions and by a game in national-level female basketball players.

Countermovement jump with arm swing results in significantly higher values for $RSI_{mod}FT$, $RSI_{mod}IMP$, and FT:CT compared to CMJ without arm swing. Additionally, strong correlations between RSIModFT, RSIModIMP, and FT:CT exist regardless of the CMJ type or testing session. Practice and game sessions have significant effects on hamstring peak torque, hamstrings to quadriceps ratio, jump height, and sprint performance in elite female basketball players during a competitive season. Higher training loads and higher amounts of game minutes negatively impact hamstring performance, sprinting ability, and CMJ jump height. These findings suggest the importance of being aware of different protocols and performance measures when assessing and comparing neuromuscular changes within and between athletes.

Impact of Training on Countermovement Metrics in Basketball Athletes. Cormie et al. (2009) investigated the impact of training on the power, force, velocity, and displacement time curves of the CMJ. Temporal phase analyses of these curves are said to provide novel insights into adaptations from a strength and power training program, respectively. This study utilized both a cross-sectional and a longitudinal design. For the cross-sectional design, subjects were grouped into either experienced jumpers (max JH >0.50m) or non-experienced jumpers (max JH <0.50m). Anthropometric measures and maximal lower body strength (1RM back squat) of each group was assessed. Following a recovery period after the 1RM back squat, countermovement jumps were then performed on a force platform. For the longitudinal design subjects either completed 12 weeks of power specific training or were part of a control group that made no changes to current daily activities. The power specific training protocol consisted of 3 training sessions over the first 14 days and progressed to 2 training sessions per week until the 12th week, respectively. During training sessions, subjects performed jump squats with approximately 30% of maximal dynamic strength or 0% of 1RM with intensity being modified so that on each rep the subjects were able to reach 98% of maximal power output of previous training or testing session.

Results from the cross-sectional examination showed that the experienced jumpers (division 1 male athletes) group had statistical increases in peak power (jumpers (J) 71.74 ± 10.69 vs. nonjumpers (NJ) 55.89 ± 7.96 W/kg), peak concentric force (J 23.39 ± 2.95 vs. NJ 20.96 ± 1.73 N/kg), peak eccentric force (J 20.80 ± 4.01 vs. NJ 18.99 ± 1.80 N/kg), peak velocity (J 3.64 ± 0.26 vs. NJ 3.02 ± 0.30 m/s), and peak displacement (J 0.58 ± 0.05 vs. NJ 0.43 ± 0.04 m) when compared to the NJ (untrained males) group. Trained division 1 male athletes can produce more power and generate greater force during a countermovement jump than untrained males. Time between peak power and peak displacement was statistically longer for jumpers (J 0.37 ± 0.03 vs. NJ 0.33 ± 0.02 s) when compared to NJ. The increase in time between peak power and peak displacement for jumpers may be a result of greater depth during countermovement. When time was normalized on the force time curve, statistically significant differences between jumpers and NJs were noted for power (90.6 to 99.8% of normalized time), for force (95.0 to 98.0%), for velocity (77.0 to 78.0%, 85.8 to 92.2%), and in displacement (85.4 to 100% of normalized time). When time is normalized, differences between jumpers and NJs occur in CMJs. Jumpers (6.02 ± 1.14 J/kg) were able to do statistically more work when compared to nonjumpers (4.63 ± 0.71 J/kg), respectively. Not surprisingly, jumpers are able to produce higher levels of work during a countermovement jump than nonjumpers.

Results from the longitudinal examination indicated a statistically increase in peak power, eccentric peak force, peak velocity, peak displacement, concentric rate of force development, eccentric rate of force development, and velocity at peak power following the power training protocol, whereas no statistically significant differences were noted for the control group. Completing a 12-week power specific training protocol increases countermovement jump performance during both the eccentric and concentric phases, respectively. When time was normalized, significant differences between the power training group and the control existed in power (29.2 to 54.6% and 60.4 to 97.4%), in force (0.0 to 16.6% and 32.3 to 62.9% and 70.8 to 81.4%), in velocity (15.2 to 39.6% and 57.2 to 78.8%), and in displacement (20.4 to 57.8% and 83.4 to 100%). Utilizing appropriately loaded jump squats in training improves absolute and temporal measures of a countermovement jump. Moreover, total power was statistically improved (pre: 72.55 ± 13.04 vs. post: 93.81 ± 21.08 W/kg) from pre to post power specific protocol training, respectively. Training type affects peak performance variables in the countermovement jump and influences the shape of the force, power, velocity, and displacement time curves. Specifically, power specific training has a positive effect on all time curves during a countermovement jump. Adaptations and impact to neuromuscular function may be different following a training protocol that does not include sport specific activities such as practice and competitions, thus understanding the impact of this additional activities is important to coaches.

A. D. Heishman et al. (2018) examined the effects of external player load and internal player readiness on performance in division 1 male basketball players. During the 5 weeks prior to the start of official practice, NCAA allows for 8 hours of strength and conditioning activities and 2 hours of basketball activities; therefore, the athletes fulfilled these time allowances by participating in basketball related activities each afternoon and performing strength and conditioning activities either in the morning or afternoon. Internal stress was monitored with the use of Omegawave technology prior to the start of each strength and conditioning session and with the use of heart rate monitors (TRIMP metric) that were worn during practice. External load monitoring was quantified with the use of Catapult OptimEye S5 which was worn during all basketball related activities. Countermovement jump height and power output, determined by the Johnson and Bahamonde equation that converts vertical jump values to peak power output, was assessed via countermovement jumps performed 3 times a week on a jump mat prior to the start of weight training sessions, respectively. The mean PlayerLoad value recorded during practice sessions was 338 ± 38.09 AU with a mean duration of 66.70 ± 32.94 minutes. A statistical ($p < .001$) increase in PlayerLoad (external load) was noted from the start of preseason (264.3 ± 5.9 AU) to the end of preseason (387.7 ± 19.7 AU). This increase in PlayerLoad paralleled an almost statistically significant ($p = .006$) increase in practice duration from the start of preseason (50.8 ± 2.9 min) to the end of preseason (71.9 ± 8.5 min). Players experienced an increase in external load in both PlayerLoad and in duration as the preseason progressed, which is appropriate to minimize risk of injury (Gabbett, 2020; Gabbett et al., 2016; A. D. Heishman et al., 2018).

Over the course of the 5 weeks, statistical decreases in power output (pre: 6,646.9 ± 171.3 vs. post: 6,419.7 ± 143.1 W) ($p < .001$) were noted; whereas decreases in CMJ height (pre: 62.8 ± 1.5 vs. post: 60.1 ± 1.6 cm) ($p = .006$), and in TRIMP scores (pre: 100.3 ± 8.6 vs. post: 81.9 ± 11.0 AU) ($p = .006$) were seen, both of which trended towards statistical significance, respectively. Neuromuscular fatigue occurred across these 5 weeks of preseason, which may be due to lack of recovery or because athletes were slightly de-trained at the start of the preseason. A decrease in TRIMP scores indicate a positive physiological adaptation and would be expected as the preseason is used to prepare athletes for practice. When specifically examining PlayerLoad, at the highest PL value, there was a statistical decrease in CMJ height (high PL: 58.1 ± 4.7 vs. low PL: 60.4 ± 5.1 cm) ($p = 0.03$), an increase in TRIMP (high PL: 135.1 ± 35.9 vs. low PL: 65.6 ± 20.0 AU) ($p < 0.001$), and an increase in duration (high PL: 115.4 ± 27.1 vs. low PL: 65.6 ± 20.0 min) ($p < .001$). Increases in duration accompany increases in PL values and positive physiological adaptations, but at the expense of CMJ capabilities in division 1 male basketball players. A statistically significant inverse relationship noted between changes in high to low PL and changes in power ($r = -0.65$; $p = 0.043$), CMJ height ($r = -0.67$; $p = 0.03$), and duration ($r = 0.95$; $p < 0.001$). When PL values increase, CMJ height and power output abilities decrease. Also worth noting is that when CNS readiness was at its highest as determined by the Omegawave, CMJ height (high CNS: 62 ± 6.5 vs. low CNS: 59.4 ± 6.6 cm; $p = 0.05$) and power output (high CNS: 6,590.5 ± 526.7 vs. low CNS: 6,383.5 ± 606.8 W; $p = 0.05$) were statistically higher than when CNS readiness was at its lowest. An athlete's ability to jump and produce power is greater when CNS readiness scores are higher. Moreover, a decrease in power output may be unavoidable during this time as both duration and frequency of basketball specific training sessions increase, thus resulting in increased levels of neuromuscular fatigue.

Ferioli, Bosio, Bilsborough, La Torre, et al. (2018) also examined changes in neuromuscular characteristics throughout a preparation period and the relationship between training load and neuromuscular performance in professional and semi-professional male basketball players. During this preparation period, training took place 5 to 12 times per week with durations of 60 – 120 minutes per session. Following a standardized warm-up, a CMJ test on a portable force platform and a repeat change of direction test to assess knee extensor strength were completed during week 1 (T1) of training and during the weeks prior to the first or second official competitive matches (T2) (Ferioli, Bosio, Bilsborough, La Torre, et al., 2018). Session ratings of perceived effort (sRPE) was used to quantify training load. Results indicated that professional players accumulated an *almost certain greater* sRPE-Training load (5058 ± 1849 AU) and training volume (909 ± 130) when compared to semi-professional sRPE-TL (2373 ± 488 AU; ES: 5.22) and training volume (587 ± 65 AU; ES: 4.68) values. Players at the professional level complete a higher amount of physical and perceived workload during a preparatory period than semi-professional basketball players. *Very likely* differences between professional and semi-professional players for absolute peak power output (ES: 1.15) and absolute peak force (ES: 1.18) were noted at T1. Professional basketball players have superior ability to produce absolute force when compared with semi-professional basketball players. Additionally, at T2 absolute peak power output (ES: 0.75) and absolute peak force (ES: 1.20) were *likely and very likely greater* for professional players. Following a preparatory training period where training volume was higher, professional players were able to maintain the ability to produce higher absolute forces when compared to semi-professional players. When examining the changes experienced between-groups from T1 to T2, small differences in absolute peak power output (ES: -0.31) and relative peak power output (ES: -0.52) were observed. A preparatory period has minimal effect on a player's peak and relative power output abilities independent of playing level. The repeat change of direction assessment resulted in an almost certain reduction in torque production (PT) dec (decrease in percentage from PT Max to PT4) for professional (27.8 ± 21.3 vs 11.4 ± 13.7%) and a very likely reduction for semi-professional (26.1 ± 21.9 vs 10.2 ± 8.2%) players from T1 to T2. PT Max (highest value of PT calculated from the peak torque-metabolic power relationship) was almost certainly increased in professional (23.5 ± 1.4 vs 25.7 ± 1.8 $W \cdot kg^{-1}$; ES: 1.46) and very likely increase in semi-professional (24.1 ± 1.7 vs 25.2 ± 1.8 $W \cdot kg^{-1}$; ES: 0.63) players. A player's ability to exercise at a higher intensity during a change of direction task was improved following the preparatory period regardless of playing level. When data was pooled to analyze within-player relationships, moderate to large negative correlations were found between training load and changes in peak power output (absolute and relative) and in all peak torques during repeat COD test except PT4, respectively.

Higher training loads may lead to an increase in negative impacts on strength and power abilities of basketball players (Ferioli, Bosio, Bilsborough, La Torre, et al., 2018). The authors note that the magnitude of effects from training volume was small-to-large (range r_s: -0.53 to -0.26) and therefore cannot be used to predict neuromuscular changes during the preparation period in basketball. The previously reviewed studies utilized time points during a basketball season that did not include competitions, the inclusion of competition and the specific stressors that can accompany competition may induce higher levels of neuromuscular fatigue.

Ferioli et al. (2020) aimed to examine changes in physical capacities of male basketball players from various teams, various competition levels, and various time points throughout the season. Players from three different levels of competition (Division I, II, and III) underwent testing at 3 separate time points throughout the season (preparatory period (T1), 2 weeks out from competitive season (T2), during competitive phase of season (T3)). Results indicated that body fat was statistically reduced after the preparation period ($P = 0.001$) and that level of play had a statistically significant effect for body mass ($P < 0.038$). Player's body fat levels are reduced following a preparatory period independent of competition level. Following the preparatory period, statistically moderate reductions were found in blood lactate levels and heart rate responses ($P < 0.001$) during the Mognoni's test, a 6-minute continuous running test performed on a treadmill (Ferioli et al., 2020). Blood lactate levels during the Mognoni's test were further reduced at timepoint 3 (competitive season) when compared to timepoint 2 (2 weeks prior to start of competitive season). Positive physiological adaptations occur following not only a preparatory period, but also during the competitive phase of a basketball season. Additionally, blood lactate ($\text{HIT}_{[\text{La-}]}$), heart rate ($\text{HIT}_{\text{HR}}$), blood hydrogen ion concentration ($\text{HIT}_{[\text{H+}]}$), and bicarbonate responses ($\text{HIT}_{[\text{HCO3-}]}$) to a HIT protocol consisting of 10 x 10s shuttle runs over a 25 + 25m with 180-degree change of direction and 20s recovery between bouts were all statistically improved from the preparatory period to the pre-competitive for each competition level. However, Division I players did show superior physiological adaptions for $\text{HIT}_{[\text{La-}]}$, $\text{HIT}_{[\text{H+}]}$, and $\text{HIT}_{[\text{HCO3-}]}$ when compared to Division II and III, respectively. Higher division players appear to have a greater capacity to adapt physiologically between the preparatory period and the pre-competitive period. These dissimilarities may exist because of differences in training age, initial levels of fitness prior to start of season, and intensity levels of training throughout the preparatory period. Moreover, positive adaptations in heart rate responses appear to occur independent of divisional playing level and may indicate a less sensitive measure of physiological adaptations throughout a training period or may be an inappropriate surrogate of fitness level in team sport athletes. Division II and Division III level players showed statistical improvements in Yo-Yo performance from timepoint 1 to timepoint 2 ($P < 0.001$). Training that occurs between the preparatory phase and pre-competitive phase during a basketball season improves players' cardiovascular fitness levels.

When examining peak power output from a CMJ, Division I players showed statistical improvement at T3 when compared to T1 (+6.97 ± 7.55%, ES =0.73, P <0.001). Because relative peak power output is dependent upon body mass, higher divisional players may experience positive body compositional changes or may participate in high quality strength and conditioning programs during a competitive basketball season. Furthermore, absolute peak power output (+3.87 ± 6.91%, ES =0.29, P <0.001), relative peak power output (+4.14 ± 4.32%, ES =0.44, P <0.001), and relative peak force (P =0.019) were statistically increased at T3 when compared to T1with no main effect of division. Power output capabilities during a CMJ improve throughout a basketball season. Lastly, absolute peak force was statistically different between Division I (2539 ± 271 N) and Division III (2166 ± 249 N) players. Upper divisional level players are able to generate higher peak forces during a CMJ, which may allow for superior performance during other basketball specific movements, such as acceleration, deceleration, and change of direction (Ferioli et al., 2020; Koyama et al., 2022; McInnes et al., 1995; A. T. Scanlan et al., 2012; Spiteri et al., 2015). Positive physiological adaptations as well as positive performance adaptations throughout a basketball season are plausible, but the level of these adaptations may be dependent upon level of competition in addition to quality of the imposed training demands. Unfortunately, the specifics of training were not discussed by the authors in this paper. Once again, the previous studies have used male athletes only and these results are not able to be generalize to female athletes with confidence.

Delextrat et al. (2012) investigated changes over the course of one week during the competitive season in strength, sprint and jump performance in elite female basketball players. Assessments were taken ~6 weeks after the start of the competitive season (mid-November). The selected week for the study was said to be representative of a typical week and included four 120-min practice sessions and one competitive game (four 10-min quarters) that occurred on the final day of the week. Each player took part in a testing session that consisted of isokinetic testing, countermovement jump, and a 20-m sprint immediately before and immediately after a practice or game. Additionally, session RPE and fluid loss was measured post practice and game. Results indicated that there was a statistically significant effect of practice and game on peak torque of the hamstrings (PTH), hamstrings to quadriceps ratio (H:Q), jump height from a CMJ, and 20-m sprint, respectively. Statistically decreases in post vs pretest values (P<0.01) for peak torque of the hamstrings was noted on day 2 (pre: 74.3 vs. post: 66.1 N·m), day 5 (79.4 vs. 70.9 N·m), and day 6 (game-pre: 77.8 vs. post: 71.6 N·m). Hamstring peak torque decreases following basketball practice sessions and a game. However, on day 3, hamstring peak torque value was statistically higher post practice when compared to pre practice values (pre: 69.4 vs. post 76 N·m). Hamstrings to quadriceps ratio statistically decreased (P<0.01) on days 5 and 6, which reflects the statistically decrease in hamstring peak torque on days 5 and 6, respectively. For CMJ performances, statistically decreases in jump height were noted on day 2 (pre: 34.2 vs. post: 29.9 cm), day 3 (pre: 33.1 vs. post: 26.6 cm), and day 6 (game-pre: 33.8 vs. post: 29.2 cm). A player’s ability to produce power is negatively affected by practice and competition (Delextrat et al., 2012). Interestingly, highest jump height was recorded pre practice on day 1 of the week (35.1 cm), which may indicate a sustained level of neuromuscular fatigue following the first practice session of the week. Statistically significant differences in pre to post 20-m sprint time was noted on day 6 (pre: 3.85 vs. post: 4.13s), which was game day. A basketball player's ability to sprint appears to be maintained following practice, but not following a competition. Also, although the increases in sprint time were not statistically significant, these increases may be meaningful in basketball where speed is important. When comparing pre-test values across the week, statistical decreases between day 3 pre-test and baseline (day 1) values for peak torque of the hamstring (day 1: 77.5 vs. day 3: 69.4 N·m) and CMJ height (day 1: 35.2 vs. day 3: 33.1 cm) were noted. These significant decreases in performance may indicate that players experience a substantial amount of fatigue following 3 consecutive practice sessions (Delextrat et al., 2012). When examining training load calculated via session RPE, a statistically significant correlation between change in PTH and training load was found on day 3 (r = -0.691) and day 6 (r = -0.602). On day 3, post-practice PTH values were higher than pre-practice values in addition to the lowest daily recorded training load occurring on day 3, respectively. A lower training load during practice may result in less fatigue of the hamstrings. On day 5, a statistically significant correlation between training load and change in H:Q (r = -0.675) and change in CMJ jump height (r = -0.599). Higher training loads and competition negatively impact a player's hamstring to quadriceps peak torque ratio as well as a player's ability to produce force via CMJ. Following higher training loads, players may benefit from extra recovery efforts. Specifically on game day, statistically significant correlations were found between playing time and changes in PTH (r = -0.603) and changes in 20m time (r = 0.705), respectively. Playing more minutes during a game will negatively impact a players ability to produce a muscular contraction and sprint when compared to playing less minutes during a game (Delextrat et al., 2012). Lastly, statistically significant correlations between frequency of jumps and change in CMJ performance (r =-0.633), sprint frequency and changes in 20-m sprint time (r = 0.705), run frequency and changes in 20-m sprint time (r = 0.601), and between high-intensity shuffle frequency and changes in H:Q (r = -0.756) were observed as determined by video recordings during competition on day 6. These results suggest that higher frequency of movements during a competition, impair a player's ability to produce force vertically or horizontally. Neuromuscular performance is altered by practice sessions and by a game in national-level female basketball players. While one week can provide insight to changes that do occur because of competition, utilizing data from a longer period of time will provide greater insight as to what changes are occurring.

Cruz et al. (2018) and colleagues sought to describe and examine the perceived training loads, recovery, and countermovement jump responses throughout 9-weeks of a competitive period in national level female basketball players. During this time, athletes participated in both technical-tactical training and strength-power training, respectively. Furthermore, the authors stated that the schedule of training sessions, which was created by the technical staff, was one that promoted balance between stress and recovery. Session RPE was collected at the end of each training session and the total quality of recovery (TQR) survey was completed by each player every morning prior to that day's training session, whereas CMJ was assessed once a week. Results indicated perceived recovery was progressively reduced when higher training loads were present. During periods of lower training as measured by sRPE, perceived recovery scores were higher (Cruz et al., 2018). Higher training loads and levels of perceived recovery have an inverse relationship in national level female basketball players. As for CMJ performance, jump height in week 1 was *likely to very likely* lower than weeks 2, 5, 7, and 8 with effect sizes ranging from

0.24 to .34, respectively. Such low effect sizes indicate that these specific weekly changes in CMJ height may not be meaningful. In week 9, the week that included the lowest overall accumulated training load, had *likely* to *almost certainly higher* jump height when compared with all other weeks. Effect sizes ranged from 0.70 to 1.10, indicating a moderate effect, which may be of importance to coaches when CMJ height is a key performance indicator. Worth noting is the steady decline in training loads over weeks 6, 7, and 8 that may have served as a mild taper and allowed players to reach highest CMJ heights in week 9. An *almost certainly higher* difference (ES: 0.67 – 2.55) in weekly training loads were noted for weeks 1, 2, and 3 when compared to weekly training loads accumulated in weeks, 4, 5, and 6. When week 1 was compared with week 6, no meaningful difference was observed. Moderate to large effects between weekly training loads were observed and training loads were higher during the initial weeks of this specific training phase. When examining the relationship between sRPE, TQR scores, and training loads, small, yet statistically significant correlations were found between sRPE and CMJ ($r = -0.28$; $P < 0.05$) and TQR scores ($r = -0.25$; $P < 0.05$). Relationships between sRPE, CMJ height, and TQR scores have an inverse weak relationship, which may illustrate the need to use a variety of data when quantifying and assessing performance and psychological recovery in female basketball players.

Several studies have explored the effects of training and external load on the performance of basketball players. Trained male athletes demonstrate higher power, force, velocity, and displacement during countermovement jumps when compared to untrained individuals. An increase in external load and training duration leads to decreased power output and countermovement jump height in basketball players. Additionally, when compared to semi-professional players, professional players can generate higher absolute peak power and higher force outputs during a CMJ. Overall, external load can influence the neuromuscular characteristics and performance of basketball players.

Impact of Training on Countermovement Metrics in Non-Basketball Athletes. R. Gathercole, Sporer, and Stellingwerff (2015) examined weekly changes in countermovement jump (CMJ) performance in elite female rugby sevens players across 6-weeks of a periodized training block. Training during these 6-weeks was included a total of 12-14 sessions per week that included speed 3x's a week, strength 3x's a week, conditioning 3x's a week, and skill work 4x's a week. Weekly CMJ testing using force plates and a position transducer occurred over the 6-weeks. Daily training loads, quantified by session-RPE, and daily wellness questionnaire examining sleep, mood, muscle soreness, fatigue, and stress, quantified by the Hooper-Mackinnon questionnaire, were also collected over the 6-weeks. Results indicated that wellness scores substantially decreased in week 3 only, whereas only small decreases were seen in weeks 3 – 6 (ES mean ± SD; ES: -0.35 ± 0.07), respectively. 23 different measures of the CMJ were examined, but only 10 were noted as displaying substantial changes throughout the 6-weeks. Substantial changes indicating perturbations in neuromuscular capacity were seen in time to peak force for weeks 3-6 (2.58 ± 0.55), peak displacement for weeks 2-6 (-2.24 ± 1.14), flight time for weeks 3-6 (-1.84 ± 0.64), and force at 0 velocity for weeks 5-6 (-1.28 ± 0.44). A combination of temporal and finite CMJ measures are affected following periodized training in female athletes. Additionally, negative changes seen in peak displacement and flight time during weeks 2-3 coincided with increases in training loads, which may indicate the sensitivity of these measures to change in accordance with changes in training load. Velocity at peak power (Wk1: 0.16 ± 1.00 vs. Wk4: -1.36 ±1.53 $m \cdot s^{-1}$) and the area under the eccentric phase of the F-V curve (Wk1: 0.60 ± 0.53 vs. Wk4: 1.02 ±1.29 $N \cdot m^{-1} Kg^{-1}$) had moderate decreases in week 4 when compared to week 1. By week 4, force production and rate of force production was negatively affected and may suggest meaningful onset of neuromuscular fatigue. Max rate of power development (Wk1: -0.11 ± 0.90 vs. Wk5: -1.48 ±1.42 $W \cdot s^{-1}$), time to peak power (Wk1: -0.19 ± 0.57 vs. Wk5: -0.86 ±.84 s), and FT:CT (Wk1: 0.24 ± 0.78 vs. Wk5: -1.97 ±1.34 s) showed a moderate to large reduction in performance at week 5 when compared to baseline. Overall, as a periodized training block progresses, changes in force production and rate of force production are impacted negatively, which may indicate the need for greater recovery efforts if increases in performance are the goal (R. Gathercole et al., 2015). Worth noting is the largest increase in training load occurred from week 2 to week 3, yet the effects of this increase in training load were not expressed by the athletes until weeks 4 and 5. Over 60% of the CMJ metrics were negatively impacted following the largest spike in training load and may illustrate the ability for trained athletes to adapt acutely to spikes in training load, but then fatigue is expressed in CMJ performance. Different sports can impose different physical stressors which will affect how the body adapts and responds.

Rowell et al. (2017) examined the impact of football match load on CMJ, testosterone, cortisol, and the testosterone:cortisol ratio. Australian football players completed a maximal CMJ and provided saliva samples during the pre-season period at 27-h and 1-h pre-match in addition to 0.5, 18, 42, 66, and 90 hours following the match, respectively. Match load was quantified via accelerometer derived PlayerLoad which was divided into three separated thresholds of low-load (0-499au), medium-load (500-1000 au), and high-load (>1000au). Results indicated that jump height, flight time:contact time, and peak velocity derived from CMJ all displayed the largest ES and t-statistic values when compared to baseline values. When examining changes in jump height at medium load, at 0.5- and 18-hours post-match, a *moderate*

(10 ± 7%) and small *likely* (7 ± 4%) reduction was displayed whereas at high load, a *very likely large* (16 ± 8%) and *moderate* (9 ± 5%) reduction were noted at the same timepoints. Jump height values appear to be dependent upon match loads when assessed at .5 and 18 hours following a match. Moreover, at the 42-hour time point, the change in jump height was unclear independent of match load. Jump height is restored to pre-match values by 42 hours post-match for all levels of match loads. When examining FT:CT at 0.5 hour post-match, a *very likely* (12 ± 7%) reduction was noted for high match loads and at 18-h post-match, a *most likely* and *likely* reduction was noted for medium and high match loads. Higher match loads lead to larger alterations in CMJ strategies, such as a decrease in flight time, when compared to lower match loads (Rowell et al., 2017). When compared to baseline values, cortisol increases at 0.5 h were *very likely* (moderate effect) in low-load, *most likely* (very large effect) in medium-load and high-load, respectively. Changes in cortisol at 18 hours post-match were *unclear* for all match load groups. Cortisol levels appear to have acute sensitivity to various match loads. As for testosterone, when compared with baseline values, *likely* increases for low and high match loads, and *very likely* increase for medium match load at 0.5 h were observed. The relationship between match load and testosterone response is not linear and is dependent upon timepoint of measurement as responses were varied following the 0.5-hour post-match time point. T:C had *likely* reduction for low-load and *most likely* reduction for medium and high loads at 0.5 h post-match. Overall, acute reductions in testosterone and cortisol levels appear to occur across all match load levels. Comparisons of change between match load levels showed a moderate *likely* greater reduction in jump height (12 ± 11%) for medium-load and large *very likely* greater reduction (18 ± 11%) in high match load when compared to low-load. Jump height measures from a CMJ decrease as match load increases in elite level football athletes. Also at 0.5 h post-

match, the high load group experienced a small *likely* greater reduction (8 ± 9%) in FT:CT when compared to medium load group. The highest match loads corresponded with the highest level of alteration in jump strategy at 0.5 h post-match. A moderate *likely* greater reduction (12.4 ± 11.8%) in FT:CT at 18 h post-match was noted for medium load when compared to low load, respectively. Athletes who experience higher match loads will sustain modifications in jumping strategy for a longer duration than athletes who experience lower match loads. Jump height and FT:CT appear to be sensitive to changes in training load and players experiencing higher match loads may need extra recovery to return to baseline CMJ height and T:C levels (Rowell et al., 2017).

Training loads and match loads influence countermovement jump performance. Higher match loads are typically associated with reduced jump height and flight time:contact time ratio. These decrements in power output highlight the importance of managing workloads loads to minimize decrements in power output abilities during a season.

Modified Reactive Strength Index

Kipp et al. (2016a) Modified reactive strength index (RSI_{MOD}) is a simplified measure that is calculated as the ratio of CMJ height to time to take-off. The modified reactive strength index indicates how much jump height is achieved relative to how much time one takes to perform countermovement and take-off during a CMJ. Specifically, a CMJ profile of high force and fast would have a higher modified reactive strength index when compared to a low force and slow CMJ, respectively. Kipp et al. (2016) investigated the validity of the RSI_{mod} as a measure of lower body explosiveness. Division 1 female volleyball players performed three maximal countermovement jumps following a sport-specific warm up and individual one-on-one skill session on a force plate. Filtered kinetic data were used to calculate jump height from flight time (JH), time to take-off (TtT), time to peak force (TtPF), concentric-phase extension range (ConROM), peak force (PF), peak rate of force development (PRFD), and peak power (PP). Intraclass correlation coefficients were as follows, 0.82 for PRFD, 0.89 for TtT, 0.86 for TtPF, 0.96 for PF, and 0.96 for PP. These CMJ metrics have good to excellent reliability levels. Data from the CMJ force-time records were entered into a factor analysis which yielded 2 factors. The initial factor, described as a speed factor, accounted for 47.2% of the variance within the data set included high loadings from TtT (0.92), TtPF (0.94), PRFD (-0.78), and RSI_{mod} (-0.50). The second factor, described as a force factor, accounted for 38.7% of the variance within the data set and included high loadings from PP (0.96), PF (0.80), and RSI_{mod} (0.84).

Because RSI_{mod} loaded onto both the speed and force factors from a CMJ, it does appear to capture mechanical characteristics that are related to both factors and can be viewed as a conceptual measure of explosiveness. Worth noting is that because RSI_{mod} loaded more strongly onto the force factor than the speed factor, this metric may be more associated with an athlete's strength levels rather than speed capabilities (Kipp et al., 2016b). RSI_{mod} captures force and speed factors when calculated from a CMJ, but it may be of benefit for coaches to be able to utilize RSI_{mod} during plyometrics other than the CMJ.

Ebben & Petushek (2010a) sought to introduce the modified reactive strength index (RSI_{mod}) to quantify the explosive nature of plyometric exercises outside of just the depth jump. The calculation of the modified reactive strength index used time to take-off in place of ground contact time as is traditionally used when calculating the reactive strength index from a depth jump. A combination of male and female subjects currently participating in division 1 athletics, club or recreational sport performed squat jumps, tuck jump (TJ), countermovement jumps

(CMJs), CMJs with 30% of estimated 1RM (DBJ), and a right leg single-leg jump (SLJ) in addition to a depth jump from a box height normalized to vertical jumping ability. When analyzing RSI_{mod}, results showed a statistically significant main effect for plyometric exercise type ($p \leq 0.001$). Quantification of RSI_{mod} is dependent upon the type of plyometric exercise that is performed. However, sex of subject did not have a statistically significant interaction with the type of plyometric exercise. When calculating RSI_{mod}, the sex of the subject does not affect the calculation, but the plyometric exercise used will affect the modified reactive strength index score. The intraclass correlation coefficients showed no statistically significant differences between RSI_{mod} values calculated from the 3 trials of each plyometric exercise.

Modified reactive strength index is reliable for a wide range of plyometric exercises, respectively (Ebben & Petushek, 2010a). The modified reactive strength index is a sensitive and stable metric that can be used to measure explosive ability in a variety of plyometric exercises.

Suchomel, Bailey, et al., (2015a) set out to assess the intrasession reliability of RSI_{mod} with using absolute and relative measures from loaded and unloaded CMJs. Moreover, the authors sought to examine relationships between RSI_{mod} and force time characteristics from the CMJ in addition to comparing the differences between male and female RSI_{mod} scores from loaded and unloaded CMJs. Division 1 female and male athletes completed unloaded CMJs and CMJs with a 20kg barbell following a standardized warm-up as part of an athlete monitoring program at the university. Reliability, from both females and males, of jump height, rate of force development, peak force, and peak power ranged from 0.92 to 0.99 during unloaded CMJs and from 0.93 to 0.99 during loaded CMJs. Typical error percentages for jump height, rate of force development, peak force, and peak power for male athletes ranged from 2.7 to 12.3% and for female athletes ranged from 1.9 to 14.7%, respectively. Overall, metrics derived from unloaded and loaded CMJs appear have a high degree of reliability. When examining the relationship between RSI_{mod} and unloaded CMJ performance variables, statistically significant correlations between RSI_{mod} and RFD ($p < 0.001$, $r = 0.56$), peak force ($p = 0.003$, $r = 0.37$), and peak power ($p < 0.001$, $r = 0.47$) were noted for male athletes. The statistically significant relationship between RSI_{mod} and RFD suggests that RSI_{mod} is a measure of explosiveness and has been supported elsewhere (Ebben & Petushek, 2010a; Suchomel, Bailey, et al., 2015a). During loaded CMJs, statistically significant correlations between RSI_{mod} and RFD ($p < 0.001$, $r = 0.56$), peak force ($p < 0.001$, $r = 0.50$), and peak power ($p < 0.001$, $r = 0.56$) were noted. The addition of load to a CMJ does not negatively impact the relationship between RSI_{mod} and explosive CMJ metrics. In female athletes, statistically significant correlations between RSI_{mod} and RFD ($p < 0.001$, $r = 0.66$), peak force ($p < 0.001$, $r = 0.50$), and peak power ($p < 0.001$, $r = 0.69$) were found during unloaded CMJs. Independent of sex, RSI_{mod} is a reliable measure of an athlete's explosive capability (Suchomel, Bailey, et al., 2015a). During loaded CMJs, statistically significant correlations between RSI_{mod} and RFD ($p < 0.001$, $r = 0.69$), peak force ($p < 0.001$, $r = 0.59$), and peak power ($p < 0.001$, $r = 0.78$). Once again, regardless of the sex of an athlete, adding load to a countermovement jump does not negatively impact the relationship between metrics of the CMJ and RSI_{mod}. Also worth noting is the stronger correlation between peak power and RSI_{mod} in females when compared with males. The female athletes in this study may have been able to produce a larger amount of force relative to body weight during CMJs. When comparing RSI_{mod} between sexes, a statistically significant difference was found in unloaded (men: 0.41 ± 0.09 vs. women 0.29 ± 0.08) and loaded CMJ conditions (men: 0.29 ± 0.07 vs. women 0.18 ± 0.06) ($p < 0.001$).

RSI$_{mod}$ is a reliable metric and can be used to measure an athlete's level of explosiveness from either an unloaded or loaded countermovement jump. Differences do exist between males and female RSI$_{mod}$ values independent of CMJ conditions, respectively. Independent of type of plyometric performed or whether that plyometric was loaded or unloaded, the ability to establish relationships between alternate performance tests and tests that generate RSI$_{mod}$ values can be of value to coaches.

Beckham et al. (2014) evaluated the relationship of RSI$_{mod}$ and isometric mid-thigh pull variables in division 1 male and female athletes. These athletes were part of an ongoing monitoring program at the university and completed unloaded countermovement jumps and isometric mid-thigh pulls on dual force platforms following a standardized warm-up at unspecified time points during the academic year. The variables of interest from the IMTP were allometrically scaled peak force (PFa; peak force · body mass$^{(0.67)}$), peak force (PF), force at 200 ms (F200), average rate of force development from 0 – 200 ms (RFD200), impulse at 0 – 200 ms (I200), and allometrically scaled force at 200 ms (F200a). Results indicated that a statistically significant relationship between modified reactive strength index and all IMTP variables was found. The overall group mean was 0.36 ± 0.10 m/s for modified RSI, 3802 ± 1053 N for peak force, 209.7 ± 45.9 N/kg for allometrically scaled peak force, 2348 ± 885 N for force at 200 ms, 65.3 ± 18.8 N/kg for allometrically scaled force at 200 ms, 6544 ± 3427 N·s$^{-1\ for}$ rate of force development at 200 ms and impulse at 200 ms was 331 ± 118 N·s, respectively (Beckham et al., 2014). Moreover, a large statistically significant correlation was found between RSImod and PFa (*r* = 0.537) and peak force (*r* = 0.509). A moderate statistically significant correlation was seen between RSImod and F200 (*r* = 0.449), RFD200 (*r* = 0.442), and IMP200 (*r* = 0.425). Isometric mid-thigh pull variables appear to have similarities with RSI$_{mod}$ (Beckham et al., 2014). A small statistically significant correlation between RSI_{mod} and F200a ($r = 0.342$) was also noted. In conclusion, explosive variables obtained from an IMTP can provide information regarding RSI_{mod}.

Suchomel et al. (2016) examined the relationships between pre-stretch augmentation percentage (PSAP), eccentric utilization ratio (EUR), reactive strength (RS), and modified reactive strength index (RSI_{mod}) from squat jumps and countermovement jumps. In addition, the authors compared 4 methods that assess lower body stretch shortening cycle ability in athletes, respectively. A combination of male and female division 1 athletes completed 2 unweighted squat jumps (SJ) and 2 unweighted countermovement jumps on dual force platforms. Pre-stretch augmentation percentage of jump height (JH) and peak power (PP) was calculated as: CMJ variable – SJ variable · SJ variable^{-1} · 100. Eccentric utilization ratio of JH and PP was calculated as: CMJ variable · SJ variable^{-1}. Reactive strength of JH and PP was calculated as: CMJ variable – SJ variable and RSI_{mod} was calculated as: CMJ-JH · CMJ-TTT^{-1}) (Suchomel et al., 2016). Results showed intraclass correlation coefficients for JH, PP, and Time to Take Off (TTT) ranged from 0.89 to 0.99%. JH, PP, and TTT derived from both SJ and CMJ are reliable. A statistically significant difference in RSI_{mod} between teams was found ($p < 0.001$). The team with the highest RSI_{mod} was men's soccer, which was statistically significantly greater than women's soccer ($p < 0.001$) and women's tennis ($p < 0.001$). A division 1 men's soccer team can produce more force in a shorter duration than division 1 female soccer and tennis teams. Men's baseball had statistically significantly higher RSI_{mod} when compared with men's tennis ($p = 0.041$), women's soccer ($p < 0.001$), and women's tennis ($p < 0.001$). Division 1 male baseball athletes can produce more force in a shorter duration than male tennis athletes, which may be due to differences in training programs. Not surprisingly, women's volleyball had statistically significantly higher RSI_{mod} values than women's soccer ($p < 0.001$) and women's tennis ($p < 0.001$). Volleyball is a sport that requires jumping high to be successful, thus a higher RSI_{mod} when compared to soccer and tennis is to be expected. Worth noting is the statistically significant strong correlation found between RSI_{mod} and reactive strength from JH ($r = 0.623$; $p \leq 0.01$). The authors noted that this strong relationship may be due to the inclusion of CMJ height in the equation, but further examination via more research needs to occur in order to examine this relationship in more depth (Suchomel et al., 2016).

RSI_{mod} is a sensitive enough measure to disseminate between teams in division 1 athletes and can be used to evaluated players' use of the stretch shortening cycle due to the inclusion of time to take off in calculation.

Bailey et al. (2014) examined positional differences between baseball players using modified reactive strength index (RSI_{mod}) during loaded and unloaded countermovement jumps. 13 pitchers and 16 positional players completed a standardized warm up followed by unloaded CMJs and CMJs with a 20kg barbell on a force plate. Along with RSI_{mod}, rate of force development (RFD) and allometrically scaled peak force (PFa) were used in data analysis. Good relative reliability with ICC values of 0.910 during unloaded trials and 0.938 during loaded trials, respectively. Coefficient of variation values were also respectable with values of 12.7% for unloaded trials and 14.2% for the loaded trials. Statistically significant differences between RSI_{mod} values from pitchers and from position players were only seen for the loaded condition ($p = 0.027$). When using RSI_{mod}, a loaded CMJ is sensitive enough to differentiate between pitchers and position players. Differences on RSI_{mod} values between these two groups, may exist because of differences in training methods and physical abilities between positions. A moderate effect size (0.81) was produced from the loaded condition. Loading a CMJ affects the outcome of the

CMJ. Additionally, RSI_{mod} had a moderate relationship to RFD in the unloaded jumps ($r = 0.48$) and was strongly correlated to the loaded jumps ($r = 0.56$). As previously mentioned in the literature, RSI_{mod} is a valid measure of explosiveness (Bailey et al., 2014; Beckham et al., 2014; A. Heishman et al., 2019; Kipp et al., 2016b; Suchomel, Sole, et al., 2015).

Position players had higher RSI_{mod} values when compared to pitchers. Position players may possess either greater levels of strength as RSI_{mod} is a metric biased towards force or a greater level of relative strength as RSI_{mod} showed moderate correlation with loaded jumps of PFa ($r = 0.44$) (Beckham et al., 2014; Kipp et al., 2016a).

Suchomel, Sole, et al. (2015) compared RSI_{mod}, JH, and TTT values from unloaded and loaded CMJs amongst six different division 1 collegiate teams. Division 1 male athletes from baseball, tennis, and soccer and division 1 female athletes from tennis, soccer, and volleyball completed unloaded CMJs and CMJs with a 20kg barbell on dual force platforms following a standardized warm-up. The modified reactive strength index was calculated by dividing jump height by the time to take off, which was calculated as the length of time between the onset of the countermovement and the point of take-off (Suchomel, Sole, et al., 2015). Results for unloaded CMJs showed statistically significant differences in RSI_{mod} between teams that were examined ($p < 0.001$). Specifically, men's soccer (0.44 ± 0.09 $m \cdot s^{-1}$) had statistically higher RSI_{mod} values than men's tennis (0.30 ± 0.07 $m \cdot s^{-1}$), women's tennis (0.23 ± 0.05 $m \cdot s^{-1}$), and women's soccer (0.28 ± 0.06 $m \cdot s^{-1}$). Male division 1 soccer players can use a shorter time to take off but produce greater amounts of force during an unloaded countermovement jump than men's tennis, women's tennis, and women's soccer of the same collegiate division. The baseball team (0.41 ± 0.08 $m \cdot s^{-1}$) had statistically greater RSI_{mod} values when compared to men's tennis ($p = 0.014$), women's tennis ($p < 0.001$), and women's soccer ($p < 0.001$), respectively. Male division

1 baseball players can produce greater amounts of force in shorter periods of time during an unloaded countermovement jump when compared to division 1 men's tennis and division 1 women's tennis and soccer athletes. Worth noting, a statistically significant difference (p = 0.001) in time to take-off was noted between men's soccer and baseball. Men's soccer (0.81 ± 0.10 s) had shorter time to take off than baseball (0.92 ± 0.08 s). Although male division 1 soccer athletes have a higher jump height during an unloaded CMJ when compared to men's and women's tennis athletes and women's soccer athletes, respectively. Although time to take-off was shorter and RSI_{mod} was higher for male soccer players when compared to baseball athletes, the baseball athletes were able to produce larger jump heights. These results may be due to differences in training styles and differences in what period of season athletes were in when the testing took place.

The women's volleyball team (0.38 ± 0.07 $m \cdot s^{-1}$) had statistically greater RSI_{mod} values when compared with women's soccer ($p = 0.004$) and women's tennis ($p < 0.001$). Division 1 female volleyball athletes can generate greater amounts of force in shorter time than division 1 soccer and tennis female athletes. When examining jump height differences among teams, baseball had statistically higher JHs (0.37 ± 0.05 m) than men's tennis (0.27 ± 0.05 m), women's tennis (0.20 ± 0.04 m), and women's soccer (0.24 ± 0.03 m). Male baseball athletes can produce larger amounts of force that result in a higher jump during an unloaded CMJ than male and female tennis athletes and women's soccer athletes. Men's soccer JHs (0.44 ± 0.09 m) were statistically greater than men's tennis ($p = 0.001$), women's tennis ($p < 0.001$), and women's soccer ($p < 0.001$). In addition, during unloaded CMJs, women's volleyball had statistically higher jump heights (0.38 ± 0.07 m) when compared with women's tennis and women's soccer . Volleyball players can jump higher than soccer and tennis players. When examining results from the loaded CMJ condition, statistically higher RSI_{mod} values were noted for men's soccer (0.30 ± 0.06 m·s^{-1}) when compared to women's tennis (0.14 ± 0.04 m·s^{-1}) and women's soccer (0.16 ± 0.04 m·s^{-1}). Unsurprisingly, male division 1 soccer athletes can produce more force during loaded CMJs than their female counterparts. Modified reactive strength index value from baseball (0.30 ± 0.06 m·s^{-1}) were statistically higher than values from men's tennis (0.22 ± 0.07 m·s^{-1}), women's tennis ($p < 0.001$), and women's soccer ($p < 0.001$). Baseball athletes can generate larger forces during a loaded CMJ than men's and women's tennis athletes and women's soccer athletes, respectively. Similar to unloaded CMJ conditions, volleyball athletes have statistically higher RSI_{mod} values (0.24 ± 0.08 m·s^{-1}) when compared to women's soccer ($p < 0.001$) and women's tennis ($p < 0.001$) athletes. Volleyball athletes can generate more force during loaded countermovement jump conditions when compared to female soccer and tennis athletes.

Results for jump heights achieved during loaded CMJs indicated that baseball athletes (0.29 ± 0.04 m) had statistically greater JHs than men's tennis (0.21 ± 0.04 m), women's tennis (0.14 ± 0.03 m), women's soccer (0.17 ± 0.02 m), and women's volleyball athletes (0.25 ± 0.07 m), respectively. The addition of load during a CMJ does not impair a baseball athletes' ability to generate higher JHs when compared to multiple other division 1 athletes. Male soccer athletes were able to generate statistically greater JHs than men's tennis, women's tennis and women's soccer. Male soccer athletes can produce more force during a loaded CMJ than men's and women's tennis and women's soccer athletes. When comparing JHs among the female division 1 teams, volleyball had statistically higher jump heights than women's tennis and women's soccer. Possibly due to the nature of the sport of volleyball and the training involved, volleyball players can jump higher than other female division 1 teams. Finally, time to take off during loaded countermovement jumps was statistically shorter for men's soccer (0.91 ± 0.10 s) than women's soccer (1.04 ± 0.14 s). Male soccer players can explode into the take-off phase of a loaded countermovement jump faster than female soccer players. In addition, it is worth noting the lack of statistically significant differences in RSI_{mod} and JHs between male baseball and male soccer athletes with female volleyball athletes. The lack of statistically significant differences may be attributed to the high volume of plyometrics often found in training programs designed for volleyball athletes and often found in the sport itself.

In conclusion, an athlete's ability to generate force in a short period of time is highly dependent upon the sport played. A coach must be aware that RSI_{mod} will be affected by an athlete's JH and the amount of time needed to generate that JH. The modified reactive strength index is a reliable measure of explosiveness. RSI_{mod} is calculated based on jump height and time to take-off. It shows a strong relationship with force and power production, including peak force, rate of force development (RFD), and peak power. Differences in RSI_{mod} values are observed between male and female athletes and can distinguish between different positions. RSI_{mod} may be a valuable tool for coaches to assess explosive capabilities in athletes.

Blood Biomarkers

Serum biomarkers can provide a systemic measure of pre and post activity or injury biochemical changes within an athletic population. The collection of serum biomarkers is far less invasive than methods used to collect other types of biomarkers such as synovial fluid biomarkers, respectively (Burland et al., 2023). Healthy cartilage turnover is a balance between catabolic and anabolic processes that can be measured via specific serum biomarkers (Bay-Jensen et al., 2010; Burland et al., 2023; Svoboda et al., 2013). Biomarkers CS846 and C2C are indicative of collagen degradation, whereas the biomarker CPII is indicative of collagen synthesis (Burland et al., 2023; Svoboda et al., 2016). Degradation of type II collagen involves excessive cleavage that creates the neoepitope, C2C, which can serve as an indicator of degradation (Aurich et al., 2017; Burland et al., 2023; Robin Poole et al., 2004). The C-propeptide of type II collagen (CPII) is produced when a C-proteinase cleaves procollagen during formation of fibrils and can be indicative of cartilage collagen synthesis (Krishnan & Grodzinsky, 2018; Månsson et al., 1995). Differences in concentration levels of these biomarkers between healthy and injured subjects has been noted in addition to pre injury and post injury levels within the same subjects (Burland et al., 2023; Cibere et al., 2009; Pietrosimone et al., 2016; Svoboda et al., 2013, 2016).

Svoboda et al. (2016) assessed the relationship between preinjury levels of 4 different serum biomarkers of collagen turnover and subsequent risk of ACL injury. These 4 serum biomarkers included 2 markers for type II collagen and aggrecan synthesis, CPII and CS846. While the other 2 markers included were markers for types I and II collagen degradation and type II collagen degradation only, C1,2C and C2C, respectively. Subjects included military active duty or cadets at the United States Military Academy and were eligible for inclusion if between 17 and 45 years old, history of traumatic knee joint injury of ACL rupture that was confirmed by an MRI. Results indicated a significant preinjury baseline difference in serum biomarker concentrations of collagen turnover between ACL-injured and control subject (Controls C1,2C 9.78 ± 1.47; ACL-Injured 10.97 ± 1.32, $p < .001$; Controls C2C 9.34 ± 1.29; ACL-Injured 10.31 ± 1.32, $p < .001$). Statistical differences in the examined biomarkers exist between individuals without and with an ACL injury. Biomarkers for collagen degradation, C1,2C (OR of 3.02, 95% CI, 1.60-5.71, $p = .001$) and C2C (OR of 2.05, 95% CI, 1.30-3.23, $p = .002$) were statistically associated with the subsequent likelihood of ACL injury when analyzed by a univariate analysis. However, when other markers were considered within the model, C1,2C and subsequent ACL injury was no longer important and removed from subsequent models, respectively (Svoboda et al., 2016). The biomarker, CPII, for collagen synthesis was statistically associated with subsequent ACL injury (OR of 4.41, 95% CI, 1.87 - 10.38, $p = .001$). These statistically significant differences in preinjury concentrations when compared with non-injury individuals may indicate that both collagen and bone metabolism differ between these groups.

Hoch et al. (2012) examined the changes in both the stability and relationship between patient reported outcomes and sCOMP levels across a spring soccer season in collegiate athletes. A combination of Division 1 male and female soccer athletes provided serum samples across 3 separate time points throughout the spring season in conjunction with completing 2 patient reported outcomes (PROs) that were used to assess knee related function and symptoms. Results indicated that when all 29 subject's data were included, a statistically significant effect of time on sCOMP levels ($P < .001$). Specifically, sCOMP values statistically increased from 1482.9 ± 217.9 ng/mL at T_1 to 1723.5 ± 257.9 at T_2 and sCOMP values statistically increased from 1482.9 ± 217.9 ng/mL at T_1 to 1624.7 ± 231.6 ng/mL at T_3. Although these increases were statistically significant, due to the minimal detectable change value of 464.6 ng/mL as calculated by the authors, the 241 ng/mL increase from T_1-T_2 and the 142 ng/mL increase from T_1-T_3 were not clinically (effect size?) significant. Six weeks of spring soccer training increases sCOMP values with no effect of sex, but these changes appear to be of no clinical significance. When 18 athletes' data were included because these subjects had data for every timepoint, a statistically significant effect for sex was noted ($P = .03$) and similar significant changes from T_1-T_2 ($P < .001$) and from T_1-T_3 ($P = .005$) were noted. These changes were not clinically significant due to the small variability in sCOMP changes. sCOMP levels change differently between males and females following 6 weeks of spring soccer training, but these changes have no true clinical significance (Hoch et al., 2012). For the PROs, a statistical increase in the Lysholm scale between T_1-T_3 ($P = .03$) occurred with higher scores equating to an excellent rating. Additionally, a statistical increase in the IKDC from T_1-T_3 ($P = .03$) and T_2-T_3 ($P = .04$) was noted. Higher IKDC scores represent fewer knee symptoms and higher levels of function (Hoch et al., 2012). Worth noting, similar to changes seen in sCOMP values, the changes in PRO scores were not clinically significant due to minimal variability. sCOMP values were altered throughout the spring soccer training season, but these changes were not clinically significant and whether increases in cartilage matrix turnover or cartilage damage occurred across an athletic season has yet to be fully elucidated (Hoch et al., 2012).

Svoboda et al. (2013) compared baseline values of select serum biomarker levels pre-ACL rupture and post ACL reconstruction. Subjects were either cadets or active-duty military who had suffered a confirmed ACL rupture and then had undergone ACL reconstruction surgery, respectively. The examined serum biomarkers included markers for both collagen and aggrecan synthesis and collagen degradation. When examining within the ACL-injured group, significant differences were observed between baseline and postinjury biomarker concentrations of C1,C2 (pre: 10.97 ± 1.32 vs. post: 9.96 ± 1.40 ng/mL, $p < .001$) and C2C (pre: 10.31 ± 1.89 vs. post: 8.98 ± 1.89 ng/mL, $p < .001$). Markers of degradation appear to decrease following ACL reconstruction. CPII, a marker of synthesis also statistically decreased from baseline to postinjury (pre: 11.09 ± 1.25 vs. post: 10.41 ± 1.44 ng/mL, $p = .002$). CPII concentration decreases after ACL reconstruction surgery when compared to preinjury concentration levels. When compared with the control group, the rate of decline was statistically greater in both type II collagen degradation biomarkers and in concentrations of C1,C2 from preinjury to post ACL injury. This higher rate of decline when compared to uninjured controls, may represent an increase in C1,C2 and CPII concentration at the joint level within the synovial fluid and not in the serum (Svoboda et al., 2016). The degradation to synthesis ratio, C2C:CPII, was statistically significantly different from preinjury to postinjury whereas this ratio did not significantly change in the uninjured controls, respectively. The C2C assay has higher specificity for the type II collagen found in articular cartilage. An ACL rupture disrupts the ratio between degradation and synthesis.

The balance between cartilage degradation and synthesis becomes disrupted following an ACL injury. This specific traumatic injury appears to elicits changes in cartilage turnover and joint metabolism (Svoboda et al., 2013).

Mateer et al. (2015) measured sCOMP levels in female division 1 collegiate soccer athletes across a spring soccer season. Six athletes provided serum samples at 10 separate time points throughout the spring season the ranged from before the spring season started until after the spring season ended. Minutes of participation in all soccer related training throughout this spring season were also quantified. Results indicated a statistically significant main effect for time, however no significant differences were found between baseline sCOMP measures and sCOMP measures at any timepoints ($P = 0.075 – 0.600$), respectively. The lack of finding statistical significance between baseline measures and all time points may be due to small sample size and high variability between or within subjects. Worth noting were the trends in sCOMP values and minutes of activity throughout the spring season. Initially, a gradual increase in sCOMP values accompanied a gradual increase in activity minutes across the first 3 weeks of spring season. However, following a one week break from soccer activities (spring break), sCOMP values showed a rapid increase (Mateer et al., 2015). Following this rapid increase, sCOMP values then plateaued over the final weeks of the season while activity minutes were at their highest. Finally, when activity minutes returned to baseline amounts, sCOMP levels decreased. It appears that there is a cumulative effect of soccer activity on sCOMP levels, but after exposure to activity has occurred, cartilage turnover holds steady. A return towards baseline levels also occurs following a decrease in activity minutes indicating that permanent cartilage damage following a single spring soccer season is highly unlikely (Mateer et al., 2015).

Conclusion

Monitoring of training load allows optimization of periodization and allows coaches to better understand individual targets for training. An optimal quantity of acute (i.e. accumulated every week) and chronic (i.e. accumulated in four-week periods) load to achieve desirable fitness may change depending on the time-point of the season. Moreover, the inequality of accumulated playing times by players that implies being exposed to different game loads may affect training targets (Vázquez-Guerrero et al., 2020). There may also be a need to report profiles according to different playing positions. The use of a countermovement jump test can be beneficial to coaches as monitoring performance during a training program or competitive season can provide insight into fatigue levels. These insights may drive modifications to training plans, workload totals, or recovery efforts dictated to the athlete. Responses to training are individual, but the questions of whether there is an inverse relationship between training loads and performance outcomes within elite women’s basketball is not clear.

Chapter 3. Monitoring External Workloads and Countermovement Jump Performance Throughout A Division 1 Collegiate Women's Basketball Preseason

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ABSTRACT

Monitoring External Workloads and Countermovement Jump Performance Throughout A Preseason In Division 1 Collegiate Women's Basketball Players

By

Michelle Lynn Van Dyke

Monitoring external workloads and countermovement jump performance may be useful for coaches. **PURPOSE**: The purpose of this study was to determine the effects of external load on player performance as measured by a CMJ and specific blood biomarkers throughout the preseason. **METHODS**:10 female division 1 basketball athletes had PlayerLoad^{TM} (PL) monitored for all mandatory basketball training during six weeks of the preseason and CMJs were performed weekly. Blood biomarkers were collected before preseason and at the end of preseason. Data were analyzed via the Catapult Sport software (Openfield, Catapult, Innovations, Melbourne, VIC, Australia) to quantify all participant movement. Data from CMJs were analyzed via Sparta Science technology (SpartaTrac; SPARTA Performance Science, v1.2.4). Cumulative effect of physical activity (CTPL) was estimated as a sum of total PL up to each jump testing session divided by the number of days. Linear mixed-effects models were used to model data related to the efficacy of PL and CTPL. Athletes (id) and their positions were examined as potential random effects. **RESULTS**: The best fit model suggested a high-order polynomial pattern between PL and the number of days since the first jump testing session with a random effect for the intercept (marginal $R^2 = 0.290$; conditional $R^2 = 0.471$). The fixed effect for the slope of the first order term was found to be positive. There was a significant negative effect of CTPL on JH ($p = 0.0037$). The boot strapped model showed a marginal R2 of 0.0183 (95% CI [0.000952, 0.0744]) and a conditional R2 of 0.884 (95% CI [0.762, 0.956]). For RSI_{mod}, a significant negative association between $\mathrm{RSI}_{\mathrm{mod}}$ and CTPL ($p = 0.0039$, 95% CI [-0.0002214, -4.597081e-05]). **CONCLUSION**: Workloads increase during preseason. CMJ height and $\mathrm{RSI}_{\mathrm{mod}}$ may have limited utility in displaying the effects cumulative workloads. Position played did not impact workload or the impact of that workload on the player. **PRACTICAL APPLICATION**: Cumulative effect of physical activity may be tracked using CTPL derived from PL. Practitioners may be encouraged to monitor alternative countermovement variables to better understand performance response to the cumulative effect of physical activity.

INTRODUCTION

Limited data exists on objective external training load in women's collegiate basketball. Ransdell et al. (2020) quantified competition workloads via inertial measurement unit data over four seasons from an elite women's Division I basketball program by player position and game outcome. It was found that guards had higher PlayerLoad per minute when compared with post players and a larger amount of higher inertial movement analysis (IMAs) were recorded during losses when compared to wins. PlayerLoad is a metric that combines instantaneous rate of change in forward (y), sideways (x), and vertical (z) acceleration and then divides it by a scaling factor of 100 (Montgomery et al., 2010). The instantaneous rate of change in these planes accumulate over the length of the respective activity to generate a PlayerLoad value (Montgomery et al., 2010). Whereas, inertial movement analysis (IMA) utilizes data from both the accelerometer and gyroscope to detect and quantify frequency of high-intensive bouts of sport-specific movement (Holme, 2015; Peterson & Quiggle, 2017). Heishman et al. (2020) characterized the external training load via IMU data in Division 1 male collegiate basketball players across a preseason. Once again, when compared to post players, guards averaged a higher training PlayerLoad value, but Playerload per minute values did not statistically significantly differ between guards and post positions. Objectively measured external training loads appear to be dependent upon position played and between competition and training (A. Heishman, Miller, et al., 2019). Moreover, comparing external training loads between males and females is difficult as differences between the sexes have been noted (Portes et al., 2020). Therefore, to help coaches design effective training plans, having a population specific and overall better understanding of external training loads may be of benefit.

In addition to quantification of external training loads, systematic jump testing has been studied extensively within athletic populations (Aoki et al., 2016; Bazyler et al., 2018; Ferioli et al., 2018, 2020; Gonzalez et al., 2013; Hakkinen, 1993; A. Heishman et al., 2020; Hoffman et al., 1991; Sams et al., 2018; Spiteri et al., 2013). Heishman et al. (2020) sought to characterize changes in CMJ flight time to : contact time ratio (FT:CT), RSI_{MOD}, and jump height across preseason training in Division 1 male collegiate basketball players. Reactive strength index modified (RSI_{mod}) has been used to capture a combination of speed-force factors and can be interpreted as a measure of lower body-explosiveness during a CMJ. This metric indicates how much jump height one achieves for how much time it takes one to flex and extend the legs during the CMJ (Heishman, Brown, et al., 2019; Kipp et al., 2016; Suchomel et al., 2015; Vieira & Tufano, 2021). RSI_{mod} is calculated as the ratio between jump height and time to take-off (Heishman, Brown, et al., 2019; Kipp et al., 2016; Suchomel et al., 2015; Vieira & Tufano, 2021) (Heishman, Brown, et al., 2019; Kipp et al., 2016; Suchomel et al., 2015; Vieira & Tufano, 2021). When intensity of external training loads were higher (PlayerLoad/min), a moderate effect for decreases in FT:CT and RSI_{mod} were noted, but no statistically significant decrements in CMJ performance occurred (A. Heishman et al., 2020). In contrast, Spiteri et al. (2013) examined levels of neuromuscular fatigue following training sessions in female basketball athletes and how fatigue subsequently affected game performance. A statistically significant decline in FT:CT ratio from baseline to post-game and from pre-game to post-game occurred, while relative power and JH had a statistically significant increase between post-game and two days post-game (Spiteri et al., 2013). Detection of neuromuscular fatigue following training appears to be dependent upon the specific jump measurements examined, thus investigating multiple outcomes of a CMJ may provide the best insight into an athlete's level of readiness or state of fatigue.

Monitoring alterations in fitness and performance characteristics within an athletic population is most effective with a combination of variables. Ideally, the use of variables that not only have a high likelihood of indicating the neuromuscular status of the athlete, but also variables that may reveal the physiological status of the athlete should be used (Edwards et al., 2018). Biomarkers that allow for objective insight to the health of cartilage may be of particular interest in female basketball athletes. Blood based collagen biomarkers CPII and CS846 are indicative of type II collagen and aggrecan synthesis, whereas biomarkers C1,2C are markers of type I and type II collagen degradation. Furthermore, biomarker C2C is indicative of type II only collagen degradation and has been shown to be suggestive of type II collagen and aggrecan catabolism (DiCesare et al., 1994; Hedbom et al., 1992; Müller et al., 1998; Svoboda et al., 2016; Verma & Dalal, 2013). These proteins have a statistically significant association with ACL tears across both an athletic season and a 4 year span in military cadets, are abundantly present in articular cartilage, and have been suggested as appropriate markers for evaluating post-traumatic OA, respectively (Hoch et al., 2012; Kaeding et al., 2017; Noehren et al., 2011; Svoboda et al., 2016).

Objective external training load data coupled with a performance test and biomarkers may help to elucidate the effects of the impact that intensified training during a pre-season period in collegiate women's basketball may have on an athlete's ability to produce power. The pre-season, because it follows a period of reduced workloads, is a critical phase for coaches and athletes. Large spikes in workloads from week to week increases the risk of injury; therefore using this time to gradually increase total workloads is imperative (Gabbett, 2020). Monitoring athletes during this period may be the difference between starting the season with multiple injuries or starting the season with athletes at the appropriate amount of weekly volume to sustain health and performance throughout the season.

Therefore the purposes of this study are to a) examine eTL values per session for the entire team and eTL values per session for guards and post player positions (eTL = PlayerLoad), b) Explore changes in CMJ performance (Eccentric RFD, RSI modified, Jump Height), and c) Explore relationships between eTL, countermovement jump performance, and in blood biomarkers (markers indicative of type II collagen and aggrecan synthesis CPII and CS846 and two markers of type I and II collagen degradation C1,2C and type II only collagen degradation C2C) across the preseason training phase in Division 1 women's basketball athletes.

METHODS

Experimental Approach to the Problem

This study took place over approximately 6 weeks of the pre-season preparation period. During this period all practices, strength and conditioning sessions, and jump testing took place as normal without any intervention by the study staff. Blood draws to examine biomarkers of collagen synthesis and breakdown took place at the beginning and end of the 6-week period. Thus, the study was mostly observational. Weight room training and jump testing were directed by the head strength and conditioning coach. To control for the effect of the time of the day, the jump testing occurred at approximately the same time each week. External training loads were measured each day with players wearing the same GPS unit in the same location on her body.

Subjects

Eleven female (age = 20.8 ± 2.0 years, height = 1.86 ± 0.07 m, body mass = 79.90 ± 10.43kg) NCAA Division 1 collegiate basketball players participated. The subjects included several national team members, multiple top-15 Women's National Basketball Association draft picks, and Collegiate All-Americans. This team won over 30 games along with the regular season conference title, conference tournament, and competed in the Sweet-16. This study was approved by the Institutional Review Board of East Tennessee State University and The University of Connecticut. All participants provided written informed consent before participating in the study.

Jump Testing

Countermovement jumps (CMJ) were completed once a week on the 2nd day following the first day back from a full day of rest for a total of 4 trials. This is the testing schedule that was set by the head strength coach. Athletes performed 4 CMJs on a commercially available piezoelectric force plate with a sampling frequency of 1000Hz (9260AA6; Kistler Instruments, Winterthur, Switzerland). Kinematic and Kinetic data analysis was completed using a proprietary software (SpartaTrac; SPARTA Performance Science, v1.2.4). Each athlete stood on the force plate prior to waiting for a visual cue to indicate stabilization of body weight and at this time the athlete completed a maximal effort CMJ. At the end of the 4 jumps, measurements from 3 trials with the 3 highest jump heights were averaged to obtain three variables: average braking rate of force development (RFD), reactive strength modified (RSI_{MOD}), and jump height (JH) from flight time. These variables were monitored during the preseason. Average braking RFD was calculated during a period of a CMJ from when the ground reaction force exceeds body weight to when the vertical velocity reaches zero (i.e. the bottom of the descent when loading for the CMJ) (Laffaye et al., 2014). Contraction time for RSI_{MOD} was calculated as the time from when the athlete's bodyweight crosses below 98% of an established steady weight mark to the point of take-off from the force plate. The steady weight mark is based on finding a 0.7s segment where the root of mean squared of point-to-point deltas is below 0.3 N (personal communication with Sparta Science Data Engineer). RSI_{mod} and JH variables have been shown to remain relatively unchanged or decrease when increases in training intensity occur and reliable when used for monitoring athletes (Cormack et al., 2008; Heishman, Brown, et al., 2019; Kipp et al., 2016; McMahon et al., 2018; Spiteri et al., 2013; Suchomel et al., 2015). Lastly, jump height calculated from flight time was used in the data analysis as this metric has been show to delineate higher level players from lower level players (Aoki et al., 2016; Ferioli et al., 2020; Scanlan et al., 2015). Jump height from flight time has also been shown to be a reliable measure (Carlock et al., 2004; Heishman, Brown, et al., 2019b; Mizuguchi et al., 2015; Moir et al., 2009). An athlete's injury status and day of CMJ trial completion was considered during statistical analysis. If an athlete participated in basketball activities, her CMJ data was utilized in analysis. Average coefficient of variation for countermovement jump variables values ranged from 4.79 to 21.20% respectively.

External Training Load (eTL) Monitoring Procedures

Athletes wore Catapult Sport OptimEye S7 Vector IMU system (Catapult Innovations, Melborne, VIC, Australia) positioned between the scapulae inside a supportive harness during every mandatory basketball training session. These devices were comprised of a triaxial accelerometer, gyroscope, and magnetometer with a sampling rate of 100Hz. Athletes wore the same IMU throughout the entire season (Heishman, Miller, et al., 2019; McLean et al., 2018). External training load monitoring began when athletes stepped on the court for basketball training sessions and ended when athletes stepped off the court following basketball training sessions. When mandatory basketball training sessions began, no substitutions were made throughout the training session, as interchanging and substituting players during play can inflate training load intensities (Fox et al., 2018; Heishman, Miller, et al., 2019). All data were analyzed using the Catapult Sport Software (Openfield, Catapult Innovations, Melborne, VIC, Australia) that utilizes algorithms to transform the input of raw inertial data captured during athlete movement into useful and standardized output variables to quantitate the movement experienced (Heishman, Miller, et al., 2019). PlayerLoad (PL) is an objective measure from the Catapult software of external training load and an overall indicator of work performed that includes changes in acceleration (forwards, backwards, upwards, and sideways) divided by a scaling factor (A. Heishman et al., 2020; Peterson & Quiggle, 2017) . A variable called cumulative effect (CPTL) was calculated as a sum of PlayerLoad (PL) up to each testing date divided by the number of days since the first day of training during the preseason period took place. In essence, CPTL serves as a density measure of practice volume up to each jump testing session, accounting for the time needed for a given amount of PL to accumulate and allowing the examination of potential relationships between practice volume and jump variables. PlayerLoad represents the daily workload variable, a summation of load vectors in the 3 orthogonal planes divided by a scaling factor and was collected by the accelerometers worn by the athletes.

Physical Activities

The sport-specific basketball practices were conducted by the team's coaching staff. The weight room training and conditioning were conducted by the head strength and conditioning coach. Weight room sessions occurred approximately 4 to 5 times during each week of the preseason (example in Table 1). Weight room sessions occurred prior to team organized basketball activity. Each session was focused on either hypertrophy, strength, or explosiveness and speed as determined by the head strength and conditioning coach. The typical duration of each session was approximately 45 minutes and progressive overload occurred across the preseason. Due to the chaotic nature of preseason, sessions were adapted based on previous day's workload level and events. Basketball specific physical activity volume was calculated via the external training load variable, PlayerLoad. Volume of physical activity was no accounted for due to daily modifications to the training plan for each athlete based on her needs for that day.

Table 1. **Weight Room Training**

DAY	EXERCISE	SETS	REPS	INTENSITY
1	DB INCLINE	3	8	10-12RM
	DB ROW	3	8	10-12RM
	NORDICS	3	6	BW
	LANDMINE RDL	3	20	20-25RM
	1-ARM DB PRESS	3	8/arm	10-12RM
	FRONT SQUAT	4	3	8-10RM
	HIGH PULL	4	4	40-60%1RM
2	HANG POWER CLEAN	6	2	60-80% 1RM
	PULL-UP	6	2	BW
	MOBILITY EXERCISES[a]			
3	JUMP SQUAT	4	5	40% 1RM
	BENT OVER ROW	4	8	10-12RM
	PULL FROM BLOCKS	4	5	60-80%1RM
	BARBELL SPLIT SQUAT	4	8	10-12RM
	INCLINE BENCH PRESS	4	8	10-12RM
	SEATED MILITARY PRESS	4	8	10-12RM
	BICEP CURLS	4	8	10-12RM
4	LATERAL SQUAT	2	8	10-12RM
	RDL	4	6	8-10RM
	RENEGADE ROW	4	6	10-12RM
	PULL-UP	4	3	BW
	ACCESSORY WORK[b]			

[a] FOCUS ON HIP INTERNAL ROTATION, HAMSTRING, ANKLE MOBILITY [b] FOCUS ON TRUNK STABILIZATION, LOWER-BODY STABILITY
Training that was often performed in the weight room during preseason.

Biomarker Collection Procedures

The initial blood draw (Off-season 1) occurred prior to the start of any mandatory pre-season activities and the 2nd blood draw occurred at the conclusion of pre-season (Preseason). All study staff involved in blood draws were trained in phlebotomy. A 10mL total blood sample was obtained from each participant through an intravenous antecubital blood draw into a standard collecting tube on site. Each of these 10mL samples collected at each time point were aliquoted/separated into 10 smaller samples of 1mL and frozen in a -80-degree freezer until the end of the season when all samples were processed simultaneously. All handling and processing of the biospecimens was conducted by trained personnel who are up to date in all Biosafety and Blood Borne Pathogen Training per EHS and BioRaft requirements at the University. Aliquots of sera (CPII, CS846, C2C) were assayed in duplicate for biomarkers of collagen turnover and metabolism through commercially available precoated enzyme linked immunosorbent assay (ELISA) kits (IBEX, IDS) according to manufacturer's guidelines. ELISA kits for each biomarker were from the same respective lot numbers to further minimize intraassay coefficients of variation. All assays for each individual subject were performed at the same time to minimize the potential effect of multiple freeze/thaw cycles.

A multilabel plate reader was used to detect serum absorbances for each cartilage turnover marker at an optical density of 450 nm. Serum concentrations were determined against the known standard curve provided by the manufacturer by utilizing Prism GraphPad Software, version 9 (Boston, Massachusetts) to plot the mean standard absorbance readings on the y-axis versus log concentration on the x-axis using a logistic equation (4 parameter). This process was performed by the same member of the research team. Average coefficient of variation values for blood biomarkers ranged from 21.45. to 58.60, respectively. The CV for CS846 levels during both Offseason 1 and the Preseason were quite large due to a medical injection one player received to help mitigate her active knee pain. This injection caused her CS846 values to show between a 144 to 176% increase over the team average CS846 value during offseason 1 and preseason, respectively.

Statistical Analysis

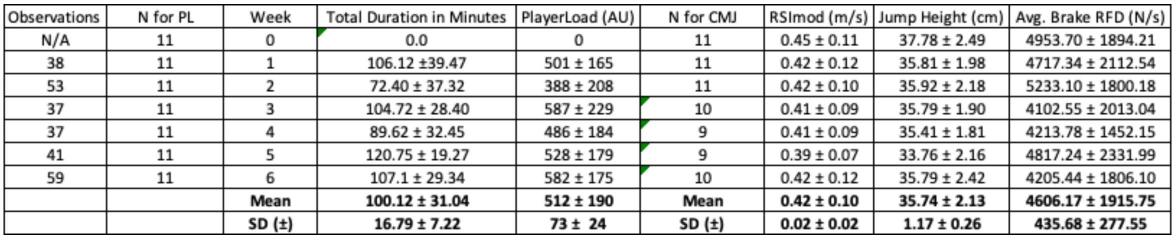
Statistical analyses were performed using R Studio (Version 2023.03.0+386; Posit Software PBC, packages used: tidyr, nlme, performance, lme4, lmeresampler,ggplot2). The critical alpha level was set at $p \leq 0.05$. Linear mixed-effects models were used to investigate trends over the course of the preseason period as well as relationships between jump variables and CTPL. Linear mixed-effects model was chosen because of the repeated nature of the observations and inconsistent number of observations per player. When a model's residuals appeared questionable (non-normally distributed, dependent residuals, and/or heteroscedasticity), non-parametric bootstrapping was used to conduct statistical inferences as well as to better estimate the model's parameters. Marginal and conditional R^2s were calculated to examine how well a model explained the variance of a given dependent variable. The blood markers of collagen degradation and synthesis were compared between before and after the preseason period using a paired sample t test. All descriptive results are reported as means ± standard deviation (SD).

Results

Preseason Overview

Due to differences in basketball specific practice schedules and injuries, the observation numbers were not consistent across all practice and testing sessions. This impacts the means and standard deviations as not all means and standard deviations were calculated always from the same set of players (Table 2).

Table 2. Team average duration and external training load per session each week. Team average CMJ performance variables each week



Observations	N for PL	Week	Total Duration in Minutes	PlayerLoad (AU)	N for CMJ	RSImod (m/s)	Jump Height (cm)	Avg. Brake RFD (N/s)
N/A	11	0	0.0	0	11	0.45 ± 0.11	37.78 ± 2.49	4953.70 ± 1894.21
38	11	1	106.12 ±39.47	501 ± 165	11	0.42 ± 0.12	35.81 ± 1.98	4717.34 ± 2112.54
53	11	2	72.40 ± 37.32	388 ± 208	11	0.42 ± 0.10	35.92 ± 2.18	5233.10 ± 1800.18
37	11	3	104.72 ± 28.40	587 ± 229	10	0.41 ± 0.09	35.79 ± 1.90	4102.55 ± 2013.04
37	11	4	89.62 ± 32.45	486 ± 184	9	0.41 ± 0.09	35.41 ± 1.81	4213.78 ± 1452.15
41	11	5	120.75 ± 19.27	528 ± 179	9	0.39 ± 0.07	33.76 ± 2.16	4817.24 ± 2331.99
59	11	6	107.1 ± 29.34	582 ± 175	10	0.42 ± 0.12	35.79 ± 2.42	4205.44 ± 1806.10
		Mean	**100.12 ± 31.04**	**512 ± 190**	**Mean**	**0.42 ± 0.10**	**35.74 ± 2.13**	**4606.17 ± 1915.75**
		SD (±)	**16.79 ± 7.22**	**73 ± 24**	**SD (±)**	**0.02 ± 0.02**	**1.17 ± 0.26**	**435.68 ± 277.55**

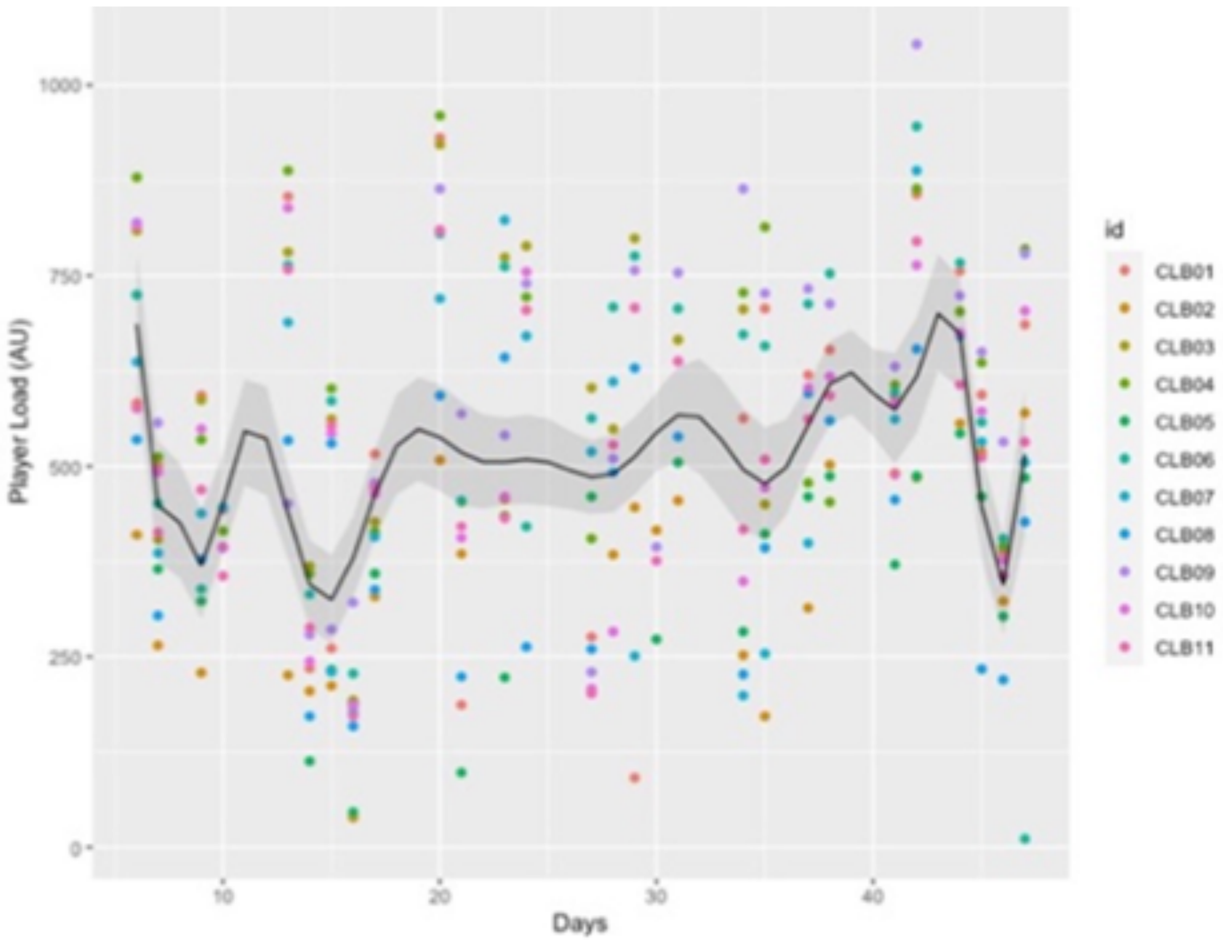
N for PL = Number of subjects that contributed to PL for that week, Week = Week of testing, Total Duration = hh:mm:ss, PL = PlayerLoad in arbitrary units (AU). N for CMJ = Number of subjects that contributed to CMJ performance variables that week, RSImod = Reactive Strength Index Modified (m/s), Jump Height (cm), Avg. Brake RFD = Average Braking Rate of Force Development (N/s). Observations = Number of court sessions that week. Mean = Grand Mean. SD (±) = Grand SD. Weekly Mean ± SD.

PlayerLoad

A linear mixed-effects model was created to examine for a trend in PlayerLoad over the data collection period (Figure 1.0). This model consisted of PlayerLoad as a dependent variable and the number of days since the beginning as an independent variable with player and position being examined as potential random effects. Due to the likely nature of fluctuations in PlayerLoad over the period, a higher-order polynomial model was examined. Due to the suspicious non-normal distribution of residuals and heteroscedasticity, non-parametric bootstrapping was applied to the model (Table 3). There was a statistically significant random effect for player on the intercept ($p < .0001$). Adding the random effect for position did not statistically improve the model for any of the slopes or the intercept ($p = 0.9999$). The first-order term in the model, had a statistically significant positive slope. The model showed a marginal R^2 of 0.290 (95% CI [0.238,0.396]) and a conditional R^2 of 0.471 (95% CI [0.393,0614]).

Figure 1.0

Daily PlayerLoad Values for Each Player



Trend of PlayerLoad over the preseason period. The solid black line shows the fixed effects of the linear mixed-effects model. The data points are color coded by player (id) as in the legend.

Table 3

Linear mixed model bootstrapped parameter estimates and 95% confidence intervals for the relationship between day (predictor variable) and PlayerLoad (response variable).*

Terms	Coefficient (95% CI)	Bias
Intercept	515.1 (486 to 564)	-0.03
day	774.3 (431 to 1128)	5.34
day^3	-598.7 (-965 to 243)	-7.87
day^5	-663.2 (-1050 to -243)	3.3
day^8	544.5 (152 to 912)	-5.27
day^{10}	841.1 (604 to 1323)	8.74
day^{13}	660.8 (310 to 999)	-1.17
day^{17}	-637.4 (-1044 to -244)	1.18

95% Confidence intervals and biases derived from bootstrap. CI = confidence interval.

Relationships between Jump Variables and CTPL

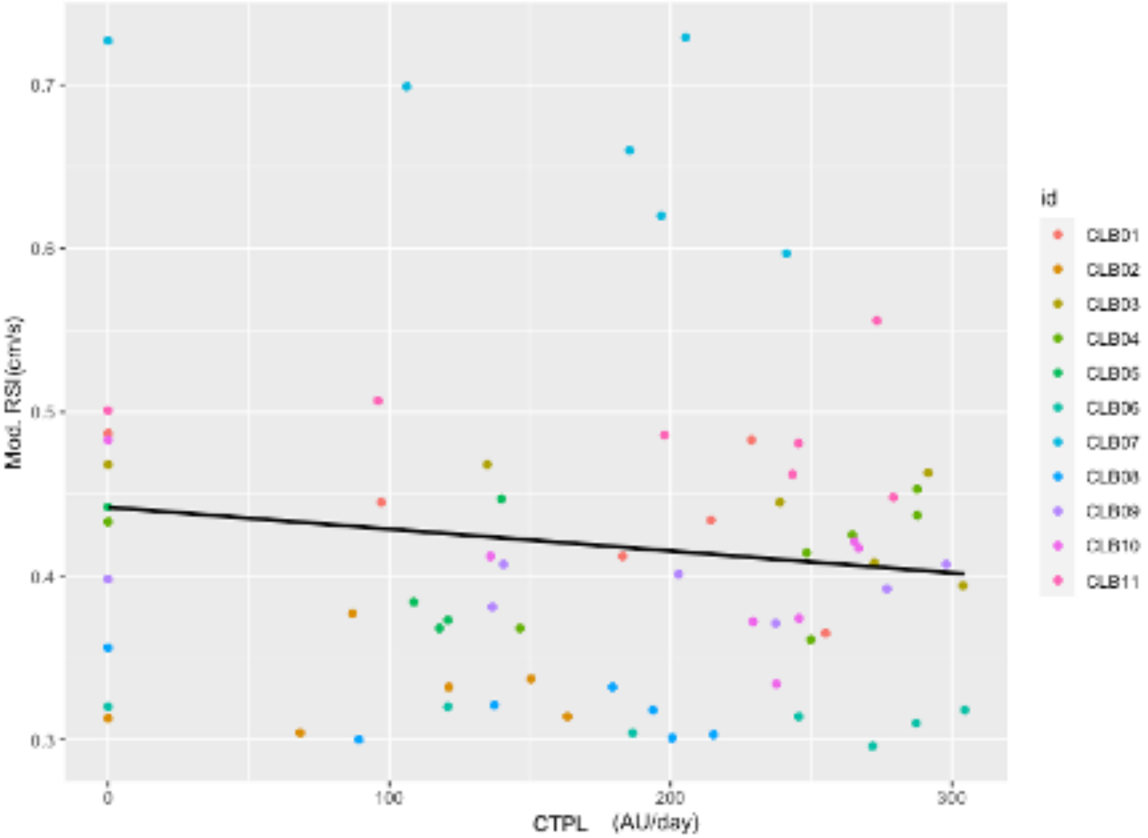
A linear mixed-effects model was created to examine the relationship between each jump variable and CTPL. The dependent variables of these models were the jump variables, and the independent variable was CTPL. Adding the random effect of player only for the intercept statistically improved the model fit for the models with RSI_{mod} and JH ($p \leq 0.0001$) (Table 4). The random effect of position did not improve the model fit for any of the models ($p \geq 0.9998$).

RSI_{mod}

The model showed a marginal R^2 of 0.016 (Bootstrap 95% CI [0.000715, 0.0906]) and a conditional R^2 of 0.898 (Bootstrap 95% CI [0.696, .961]). Relationship between RSI_{mod} and CTPL across the preseason are shown in figure 1.1.

Figure 1.1

RSI_{mod} and CTPL Values for Each Player



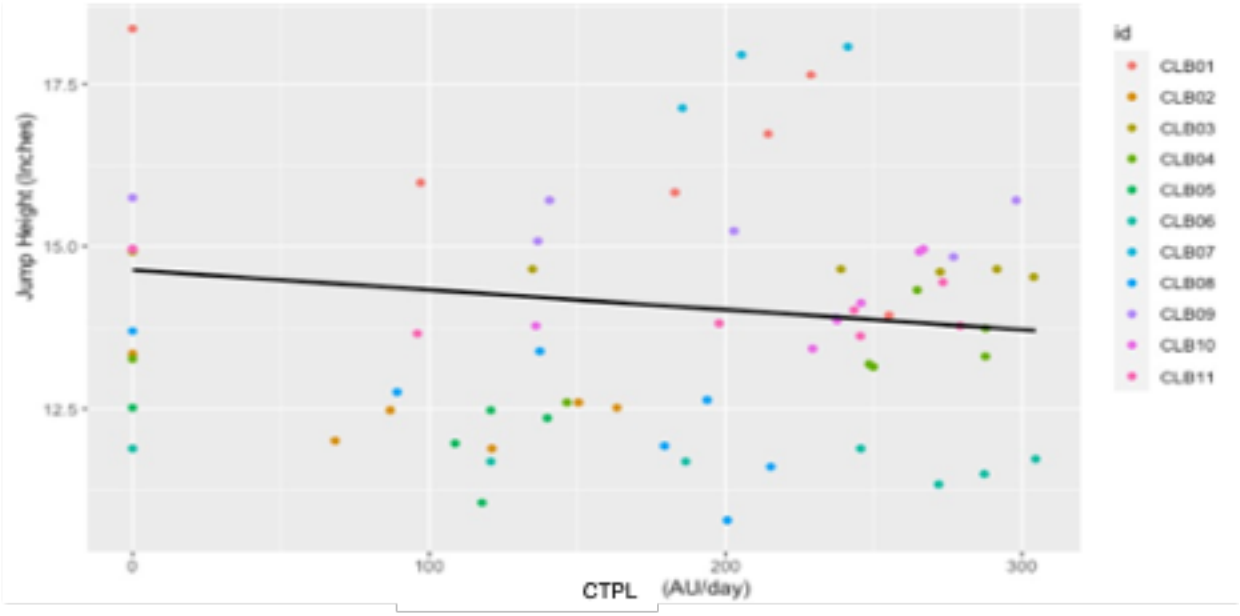
Trend of RSI_{mod} over the preseason period. The solid black line is the fixed effect. The data points are color coded by player (id) as in the legend.

Jump Height

The model showed a marginal R^2 of 0.0183 (Bootstrap 95% CI [0.000952, 0.0744]) and a conditional R^2 of 0.884 (Bootstrap 95% CI [0.762, 0.956]). (Table 4 & Figure 1.2).

Figure 1.2

Jump height and CTPL Values for Each Player



Trend of jump height over the preseason period. The solid black line is the fixed effect. The data points are color coded by player (id) as in the legend.

Table 4

Linear mixed-effects model parameter estimates and 95% confidence intervals for the relationship between countermovement jump variables (RSImod and Jump Height) and cumulative total PlayerLoad (CTPL).*

Variables	Coefficient [95% CI]	*SE*	*df*	t value	*p*
RSI_{mod} (m/s)					
Intercept	0.44 (0.38 to 5.02)	0.03	59	14.5	<0.0001‡
CTPL	-0.00013 (-0.0002 to -4.60)	0.00	59	-3.0	0.004‡
Jump Height (cm)					
Intercept	37.2 (34.0 to 40.4)	0.65	59	22.70	<0.0001‡
CTPL	-0.003 (-0.005 to -0.001)	0.001	59	-3.02	0.004‡
Avg. Braking RFD (N/s)					
Intercept	4932.83 (3829.42 to 6036.24)	559.36	59	8.82	<0.0001‡
CTPL	-0.1.81 (-4.55 to -0.94)	1.40	59	-1.29	0.201

*CI = confidence interval; df = degree of freedom; CTPL = Cumulative Total PlayerLoad.
‡Denotes statistically significant ($p < 0.05$).
Shown data are for the fixed effects.

Average Braking Rate of Force Development

The addition of average braking rate of force development as a fixed effect did not statistically improve the model from the intercept-only model (*p* = 0.1954).

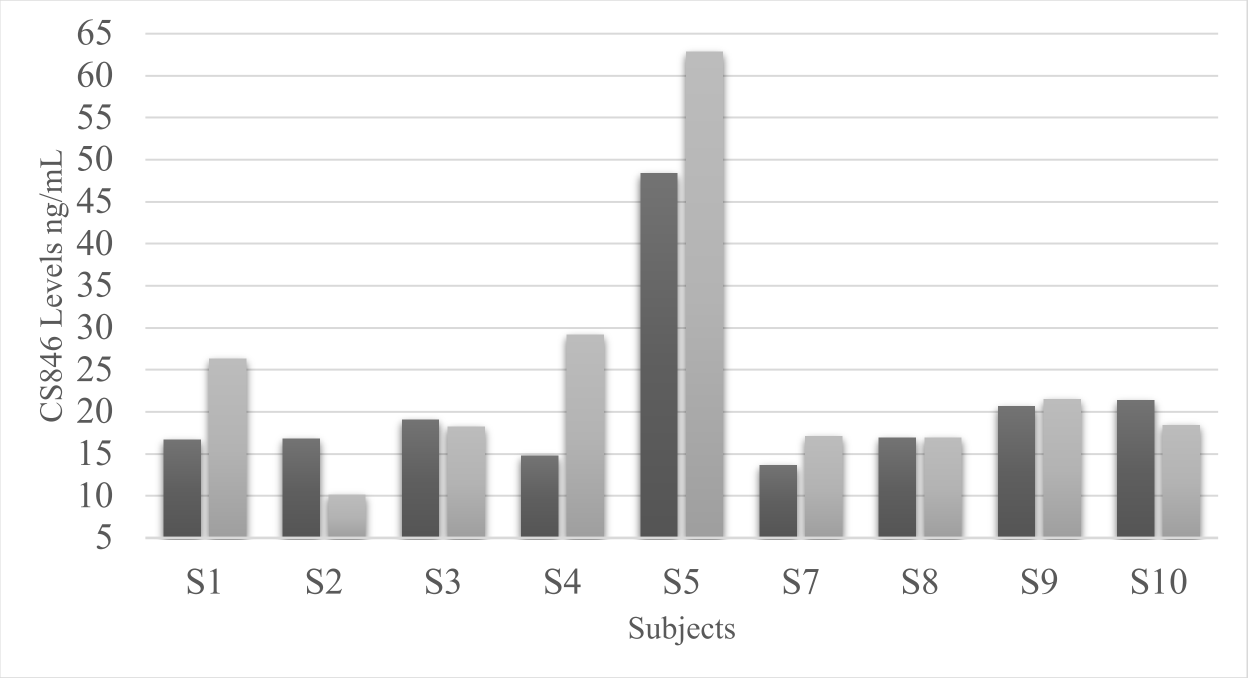
Blood Biomarkers

C2C

The Off-Season 1 values (105.30 ± 22.72 ng/mL) were not statistically significantly different from Preseason values (114.40 ± 25.54 ng/mL), t(8) = -1.9548, p = 0.08634) (Figure 2.0). The mean difference between the paired observations was -9.07ng·mL^{-1} (95% CI [-19.78, 1.63]).

Figure 2.0

Off-Season 1 and Preseason CS846 Levels (ng/mL^{-1}) Per Individual



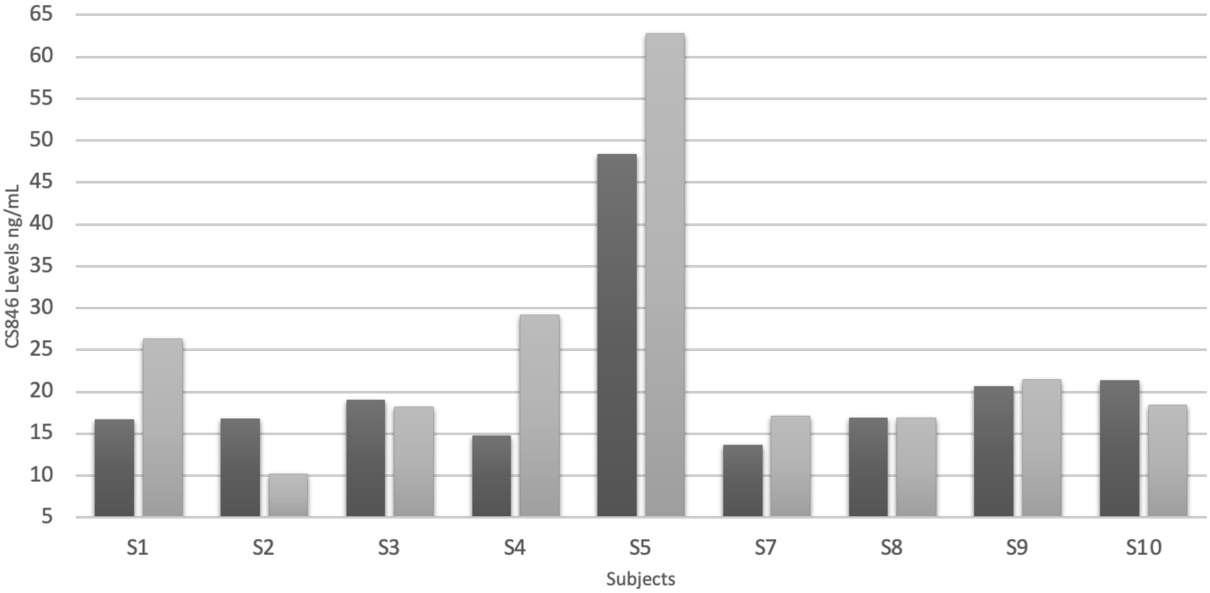
Off-season 1 and Preseason C2C Serum concentration values for each player.

CS846

The results indicated that the Off-Season 1 values (20.93 ± 10.59 (ng/mL^{-1})) were not statistically significantly different that Preseason values (24.52 ± 15.40 (ng/mL^{-1})) measurements (t(8) = -1.422, p = 0.1928) (Figure 2.1). The mean difference between the paired observations was -3.59 (95% CI [-9.41, 2.23]).

Figure 2.1

Off-Season and Preseason CS846 Levels (ng/mL^{-1})Per Individual



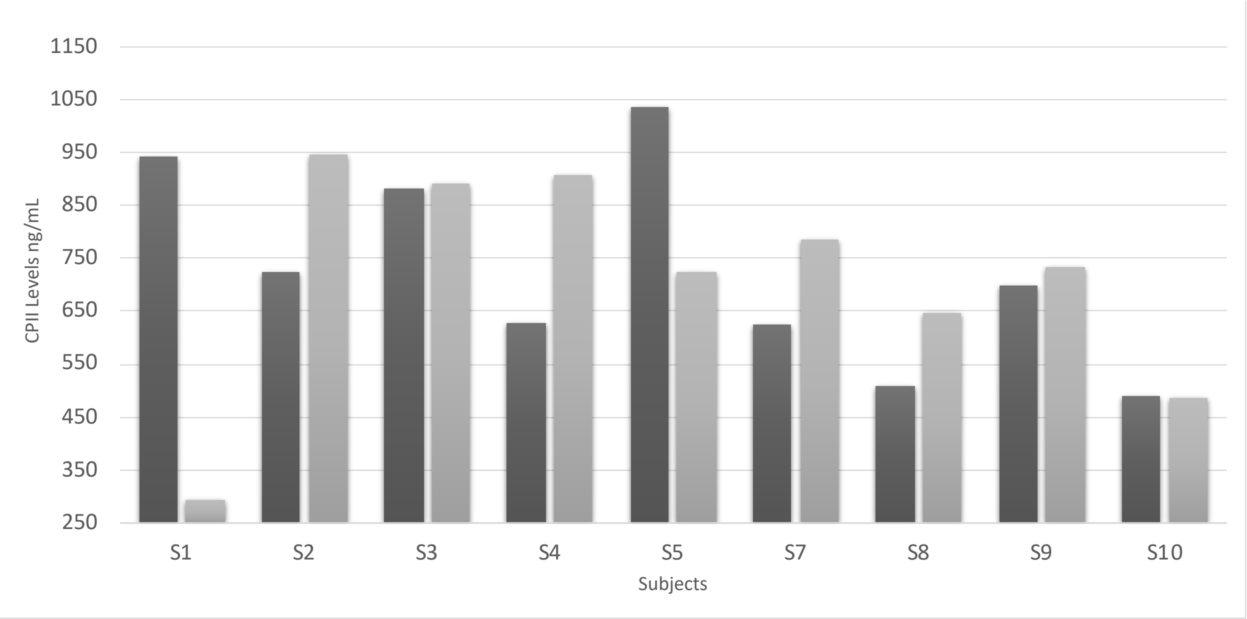
Off-Season and Preseason CS846 Levels (ng/mL^{-1}) concentration values for each player.

CPII

The results indicated that the Off-Season 1 values (725.99 ± 191.07 ng/mL^{-1}) were not statistically significantly different that Preseason values (712.39 ± 212.12 ng/mL^{-1}) measurements, t(8) = 0.1390, p = 0.8929 (Figure 2.2). The mean difference between the paired observations was 13.60 (95% CI [-212.11, 239.32]).

Figure 2.2

Off-Season 1 and Preseason CPII Levels (ng/mL^{-1}) Per Individual



Off-season 1 and Preseason CPII serum concentration values for each player.

DISCUSSION

The purposes of this study were to provide a reference point of practice volume and better understand the efficacy of select measures for monitoring performance potential and cartilage injury risks during a pre-season in elite collegiate women's basketball players. Specifically, progression and a trend of PlayerLoad as a measure of practice volume were examined over a pre-season period. In addition, relationships between select variables from weekly CMJ testing and practice volume were examined. Finally, biomarkers of collagen synthesis and degradation were compared before and after a per-season period. The primary findings of the study are that 1) practice volume is likely to show an overall trend of increase across a pre-season with some fluctuations, 2) jump height, RSI_{mod}, and braking phase RFD may not effectively reflect fatiguing effects of practice volume, and 3) it may be possible to carry out a pre-season without higher risks of cartilage injuries.

Practice volume is likely to show an overall trend of increase across a preseason with fluctuations. This is suggested by our result showing a statistically significant positive coefficient for the first order term (Figure 1 and Table 2). Our observation of an increasing trend is also in agreement with previous studies (Heishman et al., 2018; Peterson & Quiggle, 2017; Towner et al., 2023). These studies all reported higher physical activity volumes near the end of a pre-season compared to the beginning. The similar findings may be due to the realities of the design of an elite division 1 collegiate basketball season. An elite division 1 basketball season includes as many games as possible during non-conference play while also fulfilling in-conference competition requirements (Peterson & Quiggle, 2017; Ransdell et al., 2020; Towner et al., 2023). Therefore, the preseason period in basketball prepares players for a high number of non-conference games in addition to in-conference play. Strategically increasing weekly physical activity volume is meant to help reduce large spikes in physical activity volume once practice begins.

Interestingly, the observation of an increasing trend in practice volume does not appear to be influenced by position. This is supported by the lack of a statistically significant random effect for position. Comparison to previous literature is difficult as most studies either define positions differently, use different settings (e.g. practice vs. competition), or examine the team as a whole (Heishman et al., 2020; Reina Román et al., 2019; Staunton et al., 2018). However,, it appears that the positional differences are more commonly reported when physical activity volume was measured during competitions or basketball specific drills (Reina Román et al., 2019; Scanlan et al., 2012; Schelling & Torres, 2016). Nonetheless, the equivocal findings on the effect of position on physical activity volume may suggest that practices may not always be carried out with the consideration of position-specific tasks and roles during a competition and that positional physical activity demands may be team specific.

The select CMJ variables may not effectively reflect fatigue from the volume of physical activity. This finding is supported by our results of the low marginal R^2 values for the models examining the relationship with CTPL. Comparable relationships between external training loads and CMJ performances are previously reported (Heishman et al., 2020; Ellis et al., 2022; Gathercole et al., 2015). For instance, Heishman et al. (2020) found no statistically significant changes in jump height or RSImod values across a 5-week preseason in men's collegiate basketball regardless of average weekly PlayerLoad values. However, it is worth noting that Heishman et al. (2018) did find a statistically significant inverse correlation between PlayerLoad and CMJ power output ($r = -0.65$; $p = 0.043$) and CMJ height ($r = -0.67$; $p = 0.035$) in male collegiate basketball players across a preseason. This inconsistency may be partially explained by the contents, durations, and frequency of practice as these may vary substantially between coaches and teams.

There is a possibility of conducting a collegiate basketball preseason without increased risks of major injuries to cartilage. This notion is suggested by our results of the lack of statistically significant differences in the biomarkers of collagen synthesis and degradation. Biomarker changes in relation to minutes of exercise in collegiate female athletes has been examined previously. Mateer et al. (2015) found no statistically significant differences between baseline levels and levels measured at practice or postseason indicating that minutes of exercise did not negatively impact cartilage health. However, the study examined sCOMP levels and utilized division 1 collegiate female soccer players. To the authors knowledge, this is the first study to monitor levels of C2C, CS846, and CPII blood biomarkers during a division 1 collegiate basketball preseason in females. Thus, more data are needed to better understand the effects of a pre-season on potential risks of cartilage injuries.

In conclusion, practice volume may follow a general trend of increase without concomitantly increasing risks of injuries to cartilages over a preseason among elite collegiate women's basketball players. Positional differences in practice volume do not appear to be always present. Use of CMJ to monitor the fatiguing effects of physical activity volume may not be sufficiently dependable. However, findings about the effects of practice volume hinge heavily on the assumption that PlayerLoad is an effective measure of practice volume. Furthermore, it is important to note that PlayerLoad was measured only during the practice. All players engaged in other activities such as strength and conditioning sessions. Our inability to account for all physical activity volumes may have contributed to some of our observations such as the potentially trivial relationships with the CMJ metrics. To this end, continued efforts should be made to study PlayerLoad as a measure of physical activity volume. It may be beneficial to carry out more controlled experiments to compare PlayerLoad to other measures such VO^2 and mechanical work during simple tasks such as repetitive jumping might further help better understand PlayerLoad as a metric.

Practical Application

If an overall increase in practice volume is desired during a pre-season for elite collegiate women's basketball players, this may be successfully accomplished without major cartilage injuries by including fluctuations in practice volume. It is also helpful to monitor fatigue daily to ensure that the rate of recovery is not surpassed by the rate of increase in practice volume. However, CMJ (alone) may not be sufficiently effective in monitoring fatigue. Instead, or in conjunction with CMJ, sport science practitioners may consider using multiple measures of physical activity volume such as session RPE, PlayerLoad, distance covered, and/or number of jumps.

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Chapter 4. Conclusion and Direction for Future Research Conclusion

In conclusion, practice volume may follow a general trend of increase without concomitantly increasing risks of injuries to cartilages over a preseason among elite collegiate women's basketball players. Positional differences in practice volume do not appear to be always present. Use of CMJ to monitor the fatiguing effects of physical activity volume may not be sufficiently dependable. However, findings about the effects of practice volume hinge heavily on the assumption that PlayerLoad is an effective measure of practice volume. Furthermore, it is important to note that PlayerLoad was measured only during the practice. All players engaged in other activities such as strength and conditioning sessions. Our inability to account for all physical activity volumes may have contributed to some of our observations such as the potentially trivial relationships with the CMJ metrics. To this end, continued efforts should be made to study PlayerLoad as a measure of physical activity volume. It may be beneficial to carry out more controlled experiments to compare PlayerLoad to other measures such VO^2 and mechanical work during simple tasks such as repetitive jumping might further help better understand PlayerLoad as a metric.

Future Research

Future research should include monitoring of alternative countermovement jumps metrics across a longer period. Additionally, attempting to quantify physical activity and activity of daily living experience by the athletes should be included into any PlayerLoad like metric as all activity can impact levels of fatigue. Lastly, future research should include the monitoring multiple basketball teams from different leagues and levels due to the specificity of training completed by each organization and thus, limited ability to compare results.

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