ACUTE EFFECTS OF TRAINING LOADS ON FORCE PLATE METRICS

ACUTE EFFECT OF ON-COURT TRAINING LOADS ON CHANGES IN FORCE PLATE METRICS IN COLLEGE BASKETBALL ATHLETES

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TITLE: Acute effects of on-court training loads on changes in force plate metrics in college basketball athletes

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LAY ABSTRACT

This thesis explores how basketball training sessions impact athlete performance, specifically by examining neuromuscular fatigue using the countermovement jump (CMJ). The CMJ is a widely used test that measures an athlete's ability to generate force and provides insights into fatigue levels. Portable force plates were used to assess jump performance, while wearable sensors tracked the physical demands (training loads) during practices.

The study found that jump performance decreases after basketball practice, as shown by reduced jump height and changes in specific movement phases, such as slower braking and reduced force production. However, these changes were not directly linked to the amount of training load, suggesting that athletes respond to fatigue differently.

The results provide coaches and sports scientists with practical insights into monitoring athlete fatigue using force plate technology. By understanding how athletes' movement strategies change with fatigue, training programs can be optimized to manage workload and enhance recovery to enhance performance and reduce the risk of injury. This research bridges the gap between sports science and real-world applications, supporting evidence-based practices for athlete monitoring and recovery.

ABSTRACT

Basketball athletes must balance intense training demands with recovery to maintain peak performance while minimizing fatigue-related injuries. This thesis examines the acute effects of basketball practice on countermovement jump (CMJ) metrics, utilizing portable force plates to assess jump performance and inertial measurement units (IMUs) to quantify practice volume. Fourteen male athletes from McMaster University's basketball team participated, with data collected pre- and post-practice over a ten-week period. Results revealed significant decreases in performance output metrics, such as jump height and modified reactive strength index (mRSI), following practice. Additionally, phase-specific temporal metrics, including braking phase duration, increased, while driver metrics, such as eccentric mean braking force and eccentric rate of force development, decreased, indicating altered neuromuscular strategies due to fatigue. However, these changes were not significantly associated with practice volume measured by IMUs, suggesting substantial individual variability in fatigue responses.

These findings demonstrate the sensitivity of CMJ metrics to acute fatigue, particularly phase-specific force-time components, which provide deeper insights into neuromuscular adaptations beyond performance output alone. While CMJ metrics effectively capture fatigue-related changes, the magnitude of these changes does not exhibit a clear relationship to practice load, highlighting the complexity of monitoring fatigue responses in team sport settings. This work advances understanding of player fatigue and the practical application of force plate technology in sports science to inform individualized training and recovery strategies.

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LIST OF ABBREVIATIONS

BW: Body Weight

CMJ: Countermovement Jump

EMG: Electromyography

FT: CT: Flight Time to Contraction Time ratio

IMU: Inertial Measurement Unit

mRSI: Modified Reactive Strength Index

RFD: Rate of Force Development

RPE: Rating of Perceived Exertion

RSI: Reactive Strength Index

SSC: Stretch-Shortening Cycle

vGRF: Vertical Ground Reaction Force

ES: Effect Size

DECLARATION OF ACADEMIC ACHIEVEMENT

I hereby declare that the research presented in this thesis is my own work, carried out under the guidance of my supervisor, Dr. Dylan Kobsar. I have made significant contributions to the conception, design, data collection, analysis, and interpretation of the research findings.

I would like to acknowledge the contributions of my colleagues and other contributors who have assisted in various aspects of this research. Special thanks to the undergraduate students: Jasriya Ahluwalia and Anaikh Randhawa for their help with data collection and preliminary analysis.

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Chapter 1: Introduction

Collegiate basketball athletes face the need to train intensely to improve performance in their sport, while balancing the necessity of being ready to compete at peak capacity on a weekly basis. To effectively manage these potentially competing demands, it is critical to closely monitor and regulate their training load. For example, sudden and unnecessary spikes in mechanical load are recognized as risk factors for soft tissue injuries, chronic joint pain, and poor performance, as well as further detriments to health and academic outcomes (Edwards et al., 2018; Taylor et al., 2015). These excessive mechanical loads during training can result in neuromuscular fatigue, defined as a reduction in the ability of muscles to generate force due to both central (nervous system-related) and peripheral (muscle-related) factors, that ultimately impacts athletic performance (Claudino et al., 2017; Edwards et al., 2018; Enoka & Duchateau, 2016). Therefore, better understanding and monitoring levels of neuromuscular fatigue in athletes is essential for sport and strength and conditioning coaches to appropriately adjust and manipulate training volume to ensure athletes achieve an optimal balance between training adaptations and athletic performance.

While electromyography (EMG) and lab-based musculoskeletal testing protocols serve as the gold standard for assessing neuromuscular fatigue which is the reduction of a muscles ability to generate and control force, their use in day-to-day practice and competition remains impractical (Komi, 2000). As a result, strength and conditioning coaches have begun to rely on other tools, commonly found in biomechanics laboratories, to assess and monitor athletes (Gollhofer, Komi, Fujitsuka, et al., 1987; Gollhofer, Komi, Miyashita, et al., 1987; Komi, 2000). This growing integration of technology within athlete monitoring systems highlights a need for strong collaboration between academic researchers and sport practitioners. This collaboration is essential for developing evidence-based protocols that ensure the effective implementation of these technologies.

One examples is the use of portable force plates to assess changes in countermovement jump (CMJ) performance as a proxy for neuromuscular adaptations or fatigue(Alba-Jiménez et al., 2022; R. Gathercole, 2014). These devices offer an accurate assessment of the vertical ground reaction force (vGRF) during the CMJ, which provides valuable information on the overall performance of the jump, as well as the underlying kinetic qualities associated with that jump performance (Barker et al., 2018; Guess et al., 2020). Traditionally, force plate data collected in laboratory settings require customized processing scripts to analyze the force-time waveforms and extract key variables of interest surrounding the movement (Robertson et al., 2013). While this process can be time-consuming, commercially available systems have streamlined this process with real-time processing dashboards that offer instantaneously and standardized metrics relating to the CMJ. These insights can help inform coaches about changes in athlete's status, enabling timely adjustments to training or recovery strategies (Bishop et al., 2023; Claudino et al., 2017; R. Gathercole, 2014). However, the sheer volume of metrics generated by these commercially available force plates makes it challenging for coaches to select metrics that are most relevant as a proxy for neuromuscular fatigue in response to training volume.

Traditionally, performance output metrics (i.e., Jump height and Modified Reactive Strength Index; mRSI) are commonly utilized by coaches to monitor athletes (Bishop et al., 2023; Claudino et al., 2017; R. Gathercole, 2014; Robertson et al., 2013). While these metrics are easily understood by coaches and athletes, they primarily represent the overall output of the movement, namely jump height and contact time (e.g., mRSI = jump height / contact time), and may overlook critical changes in force production or timing across different phases of the CMJ (i.e., braking, amortization, propulsive). These phase-specific metrics may be more sensitive to individual adaptations associated with training volume and fatigue (Cabarkapa et al., 2023; R. Gathercole, 2014). Although phase-dependent CMJ metrics may provide greater insight into shifts in movement strategy alongside overall jump performance (e.g., jump height) as a result of increased training volume (Kennedy & Drake, 2017; Yu et al., 2020), a significant gap remains in understanding how these metrics related to training volume in applied settings during real-world sport practices (McMahon et al., 2018; Nicol et al., 2006).

Therefore, this study aimed to investigate changes in CMJ metrics obtained from commercially available portable force plates (Vald Performance – ForceDecks; Harper et al., 2020; Harper & Kiely, 2018) following on-court basketball practices with the McMaster's Men's Basketball team. Specifically, changes in performance metrics such as jump height and mRSI, as well as phase-specific metrics categorized into temporal metrics (e.g., phase timing) and driver metrics (e.g., eccentric mean braking force, concentric mean braking force, etc.), were examined before and after a typical practice session. Additionally, this study sought to examine the relationship between changes in these CMJ metrics and the mechanical loading accrued during practice, as measured by tibial-mounted inertial measurement units (IMUs), at both individual and team levels (Armitage et al., 2021; Tenforde et al., 2020; Vanrenterghem et al., 2017).

Chapter 2: Literature Review

This literature review aims to discuss key concepts essential to understanding the analysis of the CMJ and its efficacy as a proxy measurement for neuromuscular fatigue in applied sport settings. The CMJ is widely used due to its simplicity, reliability, and ability to provide ecologically valid insights into an athlete's physiological state. This review will explore the distinct phases of the CMJ, and the metrics derived from these phases, highlighting how these metrics can be used to assess fatigue and movement strategy adaptations. Furthermore, it will examine the relationship between CMJ performance and training workload, emphasizing the role of IMUs in quantifying external loads in team sports. Finally, the review will identify gaps in the literature, particularly the need to establish direct links between training load and CMJ fatigue metrics, providing the foundation for the current research.

2.1: Phases of the Counter Movement Jump

The countermovement jump (CMJ) is a widely used, simple, and reliable test for assessing athlete readiness, offering an ecologically valid measure of neuromuscular fatigue. To fully understand the parameters of the force-time wave associated with distinct phases of the CMJ, it is essential to first break down the CMJ into its component parts.

In a comprehensive evaluation by McMahon et al. (2018), six distinct phases of the CMJ were identified: (1) weighing phase, (2) unweighting phase, (3) braking phase, (4) propulsion phase, (5) Flight Phase, and (6) Landing Phase.

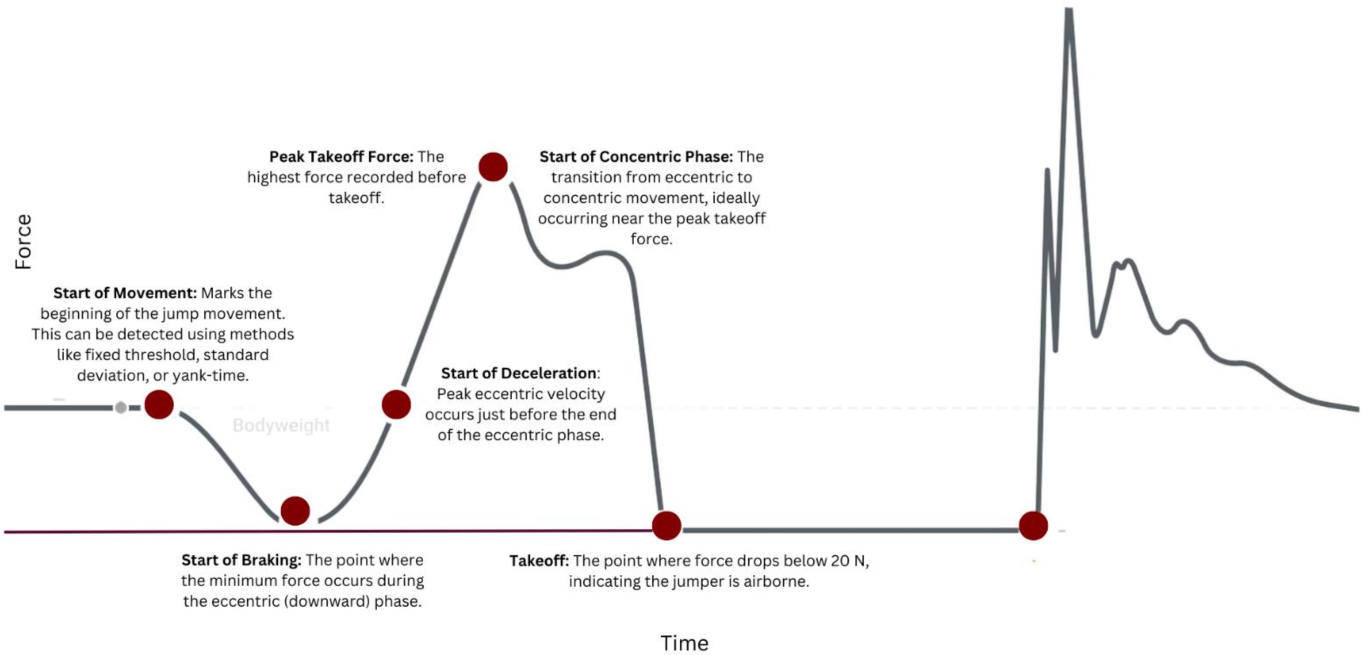


Figure 1. Phases of the countermovement jump, adopted from Vald Performance (*Key Moments and Phases of a Countermovement Jump*, 2023).

1) **Weighing Phase** – The weighing phase is critical for ensuring accurate data collection during the CMJ. During this phase, the participant stands as still as possible, allowing for precise measurement of body weight. This phase serves two primary purposes: it facilitates accurate detection of movement onset and enables calculations of subsequent metrics derived from the CMJ. Reliable measurement of body weight during this phase is essential for analyzing the force-time wave and its associated parameters (McMahon et al., 2018).
2) **Unweighting Phase (Start of movement) –** The unweighting phase begins when the athlete initiates movement through simultaneous flexion at the ankles, knees, and hips. This action lengthens the lower body musculature and marks the start of the stretch-shortening

cycle (SSC), specifically the eccentric component of the movement. Movement onset is detected by a reduction in vertical GRF below the body weight measured during the weighing phase (Eagles et al., 2015). Accurate identification of movement onset is critical, as errors at this stage can affect time-related metrics that are particularly relevant for assessing fatigue. Within the force-time wave, the unweighting phase encompasses all movement occurring before force equals the athlete's body weight.

3) **Braking Phase –** The braking phase occurs when the athlete forcefully decelerates their movement, bringing their center of mass to zero velocity. The impulse generated during this phase can vary, reflecting different approaches to braking, as it may involve a large force produced over a short duration or a smaller force applied over a longer period. This variation highlights the importance of analyzing the braking phase when interpreting force-time wave data, as it can reveal how an athlete modulates force production and adapts their movement under different conditions (McMahon et al., 2018).

4) **Amortization –** This point marks the transition between the braking to propulsion phase of movement. This phase is identified at the point in which the body COM reaches zero velocity, and a reversal of direction of the CMJ (McMahon et al., 2018).

5) **Concentric –** The final movement before the flight phase is the propulsive phase, during which the athlete aggressively reverses their motion through a forceful extension at the ankles, knees, and hips. This movement allows the leg-extensor musculature to transition into a powerful concentric action as it shortens. The onset of the propulsive phase is identified immediately after the center of mass reaches zero velocity, marking the end of the braking phase (McMahon et al., 2018).

The force at the conclusion of the braking phase is closely related to the subsequent peak force achieved during the propulsive phase. Additionally, the shape of the force-time curve during propulsion is heavily influenced by the force maintained during the transition between the braking and propulsive phases.

6) **Flight –** The flight phase begins when the athlete leaves the force plate, with the primary goal of maximizing jump height to facilitate the identification of key parameters associated with jump performance. Like the weighing phase, the most important aspect of the flight phase is the accurate identification of the take-off point.

   A commonly used threshold for determining take-off is when the measured force equals five times the standard deviation of the flight force (when the force platform is unloaded), calculated over a 300-millisecond portion of the flight phase. Accurate identification of the take-off point is essential, as errors in this calculation can lead to inaccurate measurements of jump height, affecting the reliability of downstream analyses related to the strategies employed to achieve that height (McMahon et al., 2017, 2018).

2.2: Metrics for Assessing Neuromuscular Fatigue in Athletes

Countermovement jump metric selection can be broadly categorized into two types: performance output measurements and phase-specific temporal or driver-based metrics (Bishop et al., 2023; Kozinc, 2022). Performance output measurements capture the resultant outcome of the jump, such as jump height. In contrast, strategy- or temporal-based metrics focus provide deeper insights into changes in movement strategies and the nuances of fatigue-related changes (Claudino et al., 2017; Heishman, Daub, Miller, Freitas, Frantz, et al., 2020).

A meta-analysis Claudino et al., (2017) highlighted the utility of the countermovement jump (CMJ) as a tool in athlete monitoring and assessing neuromuscular fatigue. Among CMJ metrics, the commonly utilized performance output of jump height is particularly well-researched and easily interpretable, serving as a reliable and sensitive indicator of neuromuscular fatigue. Claudino et al. found that using the average jump height across a minimum of three trials provided a more accurate assessment of fatigue status than relying solely on the highest single jump achieved during a session. Specifically, the effect size (ES) for average jump height was [ES = -0.56 (CI: -0.89 to -0.24), $p < 0.01$, $I^2 = 0.0$], compared to the ES when using only the highest jump [ES = -0.04 (CI: -0.33 to 0.24), $p = 0.76$, $I^2 = 33.5$] (Claudino et al., 2017). A potential limitation of jump height for assessing neuromuscular fatigue, is it primarily reflects the outcome of the movement rather than the strategy employed to achieve it. To gain deeper insights into an athlete's movement strategy, it is necessary to analyze metrics from various aspects of the force-time wave directly(R. J. Gathercole et al., 2015; Kennedy & Drake, 2017). The force-time wave captures the interplay between the braking and propulsive phases of the CMJ, offering a detailed view of how athletes generate and transfer force through the eccentric and concentric phase. This is particularly relevant when fatigue impairs eccentric function, often observed in high-output stretch-shortening cycle activities (Komi, 2000).

This change in movement strategy can be analyzed using the impulse (force x time)-momentum (mass x velocity) relationship, a key principle in calculating jump height. The takeoff velocity critical for determining jump height can be derived directly from force platform data. By

Jump height (Impulse=Momentum)
Force x Time = Mass x Take off Velocity (TOV)
TOV = Force x Time/Mass
Jump Height = $TOV^2/2G$

integrating the vertical GRF (upward force exerted by the ground on the body) over time, the impulse generated during the jump is calculated. This impulse is then used to determine the vertical momentum at takeoff, and used in kinematic equations, to allow for the precise calculation of jump height.

This method not only provides an accurate measurement of jump height but also enables the evaluation of force application patterns and timing, offering deeper insights into how athletes adapt their movement strategies under conditions of fatigue or altered neuromuscular function. While the calculated jump height might remain consistent between fatigued and non-fatigued states, alterations in the force-time curve reveal changes in neuromuscular strategy (Yu et al., 2020).

In a study conducted on rugby athletes, researchers assessed changes in CMJ metrics in response to acute fatigue. A major finding of the study was that athletes altered movement strategies to maintain jump height. The authors stated that this was accomplished by using longer contraction times to inflate impulse values (Kennedy & Drake, 2017). A similar finding was found in the elite snowboard cross athlete, who after a standardized fatiguing protocol decreased force production and increased jump duration (Gathercole et al., 2015). In a similar finding the authors found that jump heights were not affected by running induced fatigue, while more phase-specific kinetics and kinematics of the lower limbs were (Yu et al., 2020).

This response to acute fatigue is potentially a result of impairment to the SSC function, which follows excessive SSC activities. This impairment often manifests through longer contraction times, which serve to create greater impulses, allowing for more comparable jump heights between fatigued and non-fatigued states (Kennedy & Drake, 2017). As outlined in Robertson et al.'s *Research Methods in Biomechanics*, there are multiple ways athletes can manipulate the impulse of the force-time curve to affect jump height (Figure 2). These variations often reflect altered movement strategies induced by fatigue that jump height alone cannot reveal.

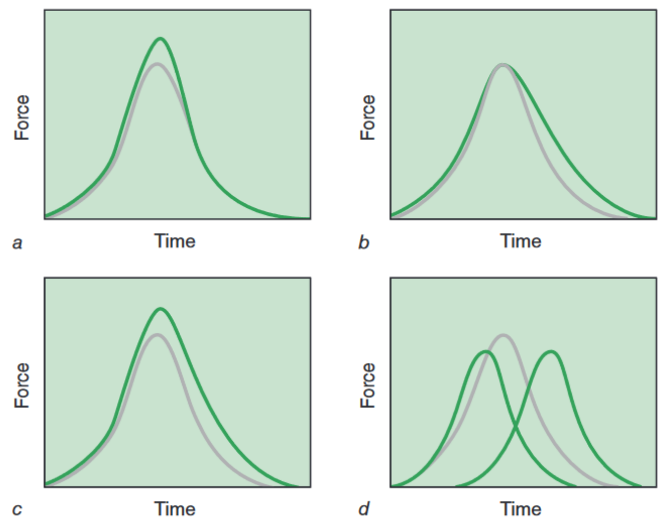


Figure 2. (a) increasing amplitude of force, (b) increasing the duration of force (c) increasing both amplitude and duration, (d) increasing the frequency or number of impulses(Robertson et al., 2013)

Utilizing metrics derived directly from phases of the force-time curve provides insight into how athletes alter movement strategy to maintain consistent performance (Alba-Jiménez et al., 2022; Bishop et al., 2023; Claudino et al., 2017). Research supports the use of time or strategy-based metrics for identifying fatigue. This is due to its effectiveness detecting compensatory movement patterns (Bishop et al., 2023; Harper et al., 2020). Metrics that include relative net impulse and flight time, have shown to be sensitive to change after fatiguing bouts of acute exercises (Bishop et al., 2023). Additionally, it is potentially useful to select metrics that can isolate distinct phases of the CMJ. This allows for phase-specific analysis jump strategy adjustments in acute fatigue states (Gathercole et al., 2015; Komi, 2000; Nicol et al., 2006). In a study completed by Gathercole et al., the authors looked at the effects of a fatiguing protocol to mimic sporting activities. They found that CMJ metrics which incorporate time within their calculation increased in the acute aftermath after a fatiguing trial (Gathercole et al., 2015). A potentially useful metric which integrates the performance output of jump height is the Modified Reactive Strength Index (mRSI). The mRSI is a ratio metric that incorporates two components of a jump test: jump height and the total time to take off or contraction time (e.g., jump height/contraction time). It is the second component of the metric that makes the mRSI an important consideration of inclusion within a robust athletic monitoring system. As "time to take off" or "contraction time" involves the time to complete all phases of the CMJ before the takeoff phase. This can provide insight into alterations into muscle actions and SSC impairments, and changes in jump strategy relative to jump height (Bishop et al., 2023; Edwards et al., 2018). In a study by Spiteri et al.(2014) the authors found that a similar ratio metric; flight time : contraction time was sensitive to fatigue. In this example, it was shown that while the jump height remained unchanged, athletes utilized a strategy in which they spend more time applying force in order to compensate for increased levels of fatigue.

These findings highlight the ability of performance outcome metrics, integrated with overall jump time to assess the underlying movement compensations in regards to increasing levels of fatigue (Komi,2000; Nicol et al., 2006; Spiteri et al., 2014). However, an important consideration when using a ratio metric, is to monitor the component parts of the metric allowing for a deeper analysis and enabling practitioners to effectively evaluate the underlying reasons for fluctuations in a variable such as mRSI. For instance, changes in mRSI may occur due to increases in jump height or reductions in time to take off (Bishop et al., 2023).

2.2.1: Phase-Specific Assessments of Countermovement Jump Force and Time Metrics

When collecting force plate data to assess jump performance, the output generated consists of force-time data (Guess et al., 2020; Robertson et al., 2013). Traditionally analysis has centered around extracting or calculating overarching discrete parameters from the data (e.g., jump height, contraction time). This results in concise and easy to interpret parameters that can be compared across subjects, however it comes at the cost of losing much of the information in the waveform (Guess et al., 2020; Robertson et al., 2013). The phase-specific force and temporal information may elude to movement “strategies” (Guess et al., 2020; McMahon et al., 2018; Robertson et al., 2013) and changes in these variables may provide a better proxy of fatigue than purely discrete performance output variables (Heishman, Daub, Miller, Freitas, & Bemben, 2020; Heishman, Daub, Miller, Freitas, Frantz, et al., 2020). In selecting metrics for analysis as proxies for fatigue, it is important to consider both phases of the CMJ and incorporate varying temporal aspects to capture changes in movement strategy. In a study done by Caparkapa et.al (2023) researchers looked at the changes in phase-specific force-time metrics following a practice intervention. The metrics used in the study were chosen by their direct relationship to phases of the CMJ that related to phases of the SSC (i.e., eccentric duration, concentric duration). It was found that all force-time related variables had significant decreases following basketball practice. A more detailed description of CMJ metrics is provided in Table 1.

Table 1. Countermovement Jump force-plate derived force plate metrics (*Customise Start of Movement Analysis*, 2024; *Key Moments and Phases of a Countermovement Jump*, 2023)

METRIC	DEFINITION
Output	
Jump Height (Imp-Mom) [cm]	Measures the vertical displacement of an individual's center of mass during a jump, calculated using the impulse-momentum theorem.
mRSI [m/s]	Jump Height / Contraction time
Strategy	
Contraction Time [ms]	The duration from the start of the jump contraction to the point of take-off during a jump.
Movement Start to Peak Force [s]	The time taken from the initiation of movement to the point where peak force is achieved.
Eccentric Duration [ms]	Phase containing negative velocity.
Concentric Duration [ms]	Time between Zero velocity until take-off.
Braking Phase Duration [ms]	Sub-phase within eccentric phase: minimum force until end of eccentric phase.
Driver	
Eccentric Mean Braking Force [N]	The average force exerted during the braking phase of the CMJ movement.
Eccentric Braking Impulse [N s]	The product of force and time during the eccentric braking phase.
Force at Zero Velocity	The force exerted at the point where velocity is zero, signalling the transition from braking to propulsion.
Concentric Impulse [N s]	The product of force and time during the concentric phase of a movement.
Concentric Mean Force	The average force exerted during the concentric phase.

2.3: The Link Between Training Load and CMJ Performance Fatigue in Basketball

The complexity and chaotic nature of applied sports science research demands that data collection be integrated into athletes' daily routine to accurately reflect the specific demands and structure of team sports. The real-world and varying training environments provides authenticity to the data being collected. Unfortunately, it also creates scientific environments with highly variable protocols and methodologies, often making comparison challenging. The following section of the literature review will attempt to summarize and critique research examining the use of the CMJ to track performance fatigue in basketball. This review of literature will first examine research with a focus on longitudinal analyses, followed by those exploring the short-term effects of practice workload on the concept of performance fatigue, and finally the concept of frequency of testing.

2.3.1: Longitudinal Analysis of Workload and Countermovement Jump Performance

A limited number of studies have examined the longitudinal dose–response relationship of workloads from an applied sport setting on CMJ performance fatigue. A study by Palmer et al. (2022) examined the influence of what they deemed, "residual neuromuscular fatigue" on the activity recorded during training activities and games in professional basketball players. The authors defined fatigue as being present in a player when flight time : contraction time decrements in the CMJ prior to training or a match were above a standardized value, determined as 0.2 times the team-wide standard deviation of flight time : contraction time, or great than a 3.1% change from a pre-season baseline. This criterion resulted in players showing "residual neuromuscular fatigue" before 16% of matches and 33% of training session. The authors then examined the effect of this incoming fatigue on the workload and intensity in the subsequent session using an IMU with a resultant acceleration algorithm for load and intensity. They found that players who were fatigued entering a match or training session displayed a lower proportion of time spent performing supramaximal activity, as compared to those who were not fatigued (p=0.02; ES=0.28). Similarly, the intensity of player movements in practice were lower when fatigue was present (p=0.02; ES=0.20), but the volume observed was not incurred was not (p=0.06). Although this work may be criticized for the arbitrary binary definition of "residual neuromuscular fatigue" as 0.2 standard deviations from a pre-season baseline, and the limited ES observed, these findings still provide support for the relationship between CMJ performance decrements, fatigue, and training load.

Alternatively, the relationship between CMJ performance decrements and fatigue was not as clear in a recent study by Murr et al. (2023). In this study, the authors examined the long-term changes in CMJ metrics (e.g., jump height, time to take off, mRSI) as markers of "neuromuscular readiness" over the length of a collegiate basketball season. The authors had athletes (n = 9) complete a CMJ testing protocol prior to the start of practice over 18 weeks of a competitive schedule, including 34 games (~2 per week). During the study, researchers assessed the changes in CMJ metrics from the beginning of the season to the post-season. Overall, they found that the only significant change observed over the course of the competitive season was an increase in jump height (44.6 cm pre-season to 47.8 cm post-season; p=0.13; ES=1.1). Unfortunately, not only did the authors not directly examine the effect of practice workloads in any way, but they also failed to conduct a comprehensive longitudinal analysis of the data. The data presented and statistical comparisons made were only that of the first and last week of collections (i.e., pre-season vs. post-postseason). While it may be expected fatigue is present at the end of an 18-week, 32 game season, and as such these data do not support that, it should also be noted that there was a significant increase in body weight at post-season. This suggests that rather than a fatigue effect through the season, this specific cohort may have improved body composition and CMJ performance instead.

Finally, and perhaps most comprehensively, a study by Heishman et al. (2020), examined changes in external training load alongside changes in CMJ performance during the pre-season preparation period for Division I basketball players. In this study, the researchers conducted weekly CMJ tests prior to the start of a weightroom training session, as well as external training load from 22 on-court practice over the course of 5 weeks using an IMU. The authors found practice workload declined following the initial two weeks. While no significant changes were observed in the CMJ metrics over the 5-week pre-season, the authors did note that flight time : contraction time and mRSI were trending towards a decline (i.e., moderate effect size but not significant) following the initial two weeks of high practice workload. Unfortunately, the authors failed to conduct any statistical tests to examine the direct relationship between workload and CMJ variables. Moreover, this finding highlights the challenges with applied sport research outlined initially, as the reduction in workload observed after week 2 may have been in response to what coaches were intuitively observing in their athletes. In other words, the changes in practice load may have been a strategic approach by the coaches to stave off fatigue in their athletes. Regardless, while there appears to be some evidence supporting the longitudinal relationship between CMJ fatigue metrics and workload across the above studies, the variable methodologies used, and inconsistent findings suggest a need to examine this relationship more comprehensively, or in a more direct, short-term manner.

2.3.2: Acute Analysis of Workload and Countermovement Jump Performance

The previous section highlighted longitudinal studies, which examined the long-term effects of practice volume on CMJ testing and performance fatiguability. However, a more direct approach may be to examine the immediate drop-off in CMJ performance following a specific workload observed in practice. Spiteri et al. (2014) provided evidence for this direct relationship as they examined changes in CMJ performance before and after training sessions and games. Testing occurred over the span of a week in which there were two training sessions followed by one game, with jumps being performed both before and after each training session and game. Metrics used to assess performance were jump height, flight time : contraction time, and relative power (W/Kg) (Spiteri et al., 2014). Testing included a 10-minute warm-up followed by the execution of three CMJS. Significant changes observed in flight time : contraction time suggested that it may be a sensitive measure to monitor neuromuscular fatigue (Spiteri et al., 2014). Additionally, there were significant changes throughout the week as athletes accumulated fatigue from baseline to pre-game and post-game scores. Interestingly, in line with previous findings, jump height remained relatively unchanged. The authors suggested this was a result of athletes increasing impulse to overcome neuromuscular fatigue (Spiteri et al., 2014). This paper looked to examine the fatigue associated with single bout of practice along with accumulation of fatigue within a practice week. Conclusions of this paper are in line with what is known about fatigue and the resulting alterations in movement strategy. This highlights the importance of maintaining a strategy metric within the assessment of neuromuscular fatigue.

In a separate study by Petway et al. (2021), the authors assessed in game performance and its relation to a repeated jump test completed 1 day before a game to determine whether there was a degradation in neuromuscular performance, or alternatively, a potentiation effect resulting in improved neuromuscular performance from practice. A total of 17 games were evaluated with 7 athletes. A repeated hop test was used to determine neuromuscular performance. While this is not equivalent to the CMJ test, it was completed on a force plate that allowed for the evaluation of jump height and RSI. To evaluate pre-game jump performance, 1-day before game day termed “Match Day-1”, participants completed jump testing. This occurred at the start of a scheduled practice and after the completion of a standardized warm-up. Within 15 minutes of the completion of practice post jumps were recorded. To determine in-game performance peak in-game speed was evaluated, with the use of spatial tracking cameras. Performances were categorized into slow and fast based on a median split analysis, where a fast and slow performance was determined based on score above and below their median values of peak speed achieved in game. Important findings were that participants who achieved higher gains in RSI scores at match day-1 testing also had higher peak in-game speed scores. This is important because it highlight the potential of a potentiation effect that may occur during practice before game day. While providing evidence that repeated jump ability can provide insight into athlete readiness prior to competition. Furthermore, jump height was not sensitive to differences between faster and slower performances. Although an interesting and important paper, a missing component of this analysis, and many in this area, is the quantification of workloads alongside potential changes in CMJ metrics related to fatigue.

2.4: Intersection of Workload and Performance Fatigue

As alluded to in earlier sections, monitoring the accumulation of fatigue is a key component of the training process. However, in applied sport settings, comprehensive assessments of neuromuscular fatigue using traditional, in-lab approaches is often impractical. Therefore, the more accessible CMJ test can serve as a valuable proxy for performance fatigue. A key focus of this thesis is establishing a direct relationship between CMJ metrics of fatigue and the actual workload experience by athlete in a dose-response manner. Thus, it is essential to discuss the concept of workload in the context of athletic performance.

2.4.1: External vs. Internal Workload

Athletes undergo training with the intention of eliciting a specific training response, the applied training stimulus is defined as the training load (Impellizzeri et al., 2019). Training load is often categorized into external and internal training loads. The external training load, representing the quantifiable work done by athletes, such as the distance covered in practice or the total number of accelerations, is the prescribed training designed to elicit a training response (Impellizzeri et al., 2019). The response to the prescribed training is defined as the internal training load (Impellizzeri et al., 2019). The internal training load, measured through a variety of means such as the Borg 10-scale and heart rate monitors, reflects an individual's unique response to a prescribed training stimulus. An important factor to consider is that each athlete's internal response to a given training load is unique, with variations in response to the same training load across individuals (Borg, 1998; Gómez-Carmona et al., 2020).

2.4.2: Measurement of External Workload & Internal Workload

During sport practice the quantification of external workload can be accomplished using wearable technology. The main pieces of equipment include torso-mounted GPS units or tibial mounted IMUs (Armitage et al., 2021; Edwards et al., 2018; Gómez-Carmona et al., 2020). Torso mounted GPS units are used to derive metrics of workload by tracking the amount and intensity of player movement on the field (Barrett et al., 2014). While these units have been shown to be reliable in measuring external volume, they are not without their limitations. For instance, they are not a viable option indoors where GPS signals are compromised. Additionally, as these are torso worn units (Armitage et al., 2021; Tenforde et al., 2020), they may not provide a direct measure of lower body loading, which for the sport of basketball movements, shuffling, backpedalling, short accelerations would be the most relevant to track (Montgomery et al., 2010). This provides a need for the use of tibial-based accelerometers for team sport athletes allowing for the assessment of loading rates of the lower body more accurately during indoor sports like basketball. One of the most used tibial mounted IMUs for this use case is the iMeasureU Blue Trident sensor that offers a dual-g sensors (e.g., low-g at a range ±16g and a frequency of 1,125Hz and high-g at a range of ±200g at a frequency of 1,600 Hz) and the associated software to calculate impact load as the accumulated resultant acceleration with each step taken (Burland et al., 2021). Research has found the use of this technology to display good to excellent reliability (intraclass correlation coefficients 0.75-0.89) in measuring sport-specific movement patterns as a cumulative impact for acceleration-deceleration, plant and cut, and change of direction tasks between sessions(Burland et al., 2021).

Another important component of workload measurement is internal training load. Internal training load measurement can be measured using self-report questionnaires which asks the athlete to rate the intensity level of their exercise, often presented as the modified Borg-10 Rating of Perceived Exertion scale (RPE) (Borg, 1998). Further combining this questionnaire with training duration yields the Session RPE (Impellizzeri et al., 2019). This is calculated by multiplying training duration by the RPE score, thereby offering a quantifiable metric into an athlete's perceived exertion and internal workload in arbitrary units (Fusco et al., 2020; Impellizzeri et al., 2019; Inoue et al., 2022).

2.4.3 Inertial Measurement Units to Monitor Practice Volume

Quantifying external mechanical load is crucial in athlete monitoring systems. Technological advancements, such as IMUs equipped with accelerometers, enable the measurement of mechanical load in real-world scenarios. IMUs capture resultant accelerations, offering a proxy for mechanical loading. Although laboratory-grade accelerometers offer high accuracy, automatically generated metrics are essential for meeting the real-time data needs of coaches and clinicians (Armitage et al., 2021; Tenforde et al., 2020). Tri-axial tibial accelerometer units (IMeasureU Blue Trident) allow for the with associated data processing (IMU Step dashboard) provide automatically generated external biomechanical load metrics of step count, impact load, and average intensity. For context, impact load is the sum of the peak resultant acceleration in g from each step and is therefore directly proportional to the number and intensity of impacts, while average intensity is the mean average impact intensity derived from every impact propagated into the Left leg or the Right leg (Armitage et al., 2021; Tenforde et al., 2020).

2.5: Literature Review Summary

The outlined literature review highlights the relationship between workload, CMJ performance and fatigue. A missing component is the lack of a studies to directly compare the workload with these decrements (or potentiation) in performance. This provides the basis for the main goal of this thesis that explores the relationship between practice volume or training load, as measuring by IMUs, and its impact on CMJ fatigue metrics across individual sessions. The unique component of my research will examine the immediate changes between pre and post practice changes in chosen metrics while also tracking changes over a six-week preseason period. While also adding to the body of literature surrounding established metrics of monitoring performance fatigue (i.e., jump height, mRSI).

Chapter 3: Research Questions and Hypotheses

This study aimed to examine the effects of on-court basketball practices on CMJ performance as a marker of neuromuscular fatigue, in collaboration with the McMaster Men's Basketball team during their 2022-2023 preseason. In doing so, the following research questions were addressed:

Research Question 1: In male collegiate basketball players, do on-court basketball practices elicit changes in CMJ a) performance output metrics (jump height and mRSI), b) phase-specific temporal metrics (e.g., phase durations), and c) phase-specific driver metrics (e.g., peak force, mean force, impulse).

Hypothesis 1: *Significant changes will occur in all CMJ metrics following practice sessions, with more pronounced changes observed in phase-specific metrics compared to performance output metrics.*

Research Question 2: Is there a significant association between practice workload, as measured by IMUs, and the magnitude of changes in the CMJ metrics?

Hypothesis: *There will be a significant association between practice workload and phase-specific CMJ metrics, such that higher training loads will result in greater changes in these metrics.*

Chapter 4: Methods

4.1: Study Design

This study employed a repeated measures observational research design in direct collaboration with the Men's Basketball team at McMaster University. Pre- and post- practice CMJ data were collected using portable force platforms twice weekly for a period of ten weeks during the pre-season September 10th, 2023 – December 10th, 2023. Additionally, on-court training load was estimated using wearable IMUs placed on the lower limbs of each participant prior to each practice.

4.2: Participants

Fourteen male collegiate basketball athletes from McMaster University participated in the study. The sample included eight forwards (age: 21.3±1.5 height: 198.5 ± 4.3 cm, mass: 91.7 ± 13.1 kg) and six guards (age: 21.2 ±1.2, height: 185.6 ± 6.4 cm, mass: 75.2 ± 7.0 kg). All participants were members of the McMaster Men's Basketball team and were cleared for participation by McMaster's certified athletic therapists for the 2023-2024 competitive season. Ethical approval for this study was obtained from the McMaster Research Ethics Board (MREB-5491), and all participants provided informed consent prior to participation. Given the limited pool of potential participants, constrained by the size of the McMaster Men's Basketball team roster, no sample size calculation was performed. This limitation is acknowledged as a constraint of the study.

4.3: Data Collection

Prior to practice, participants were fitted with two wearable IMUs (Vicon IMeasureU, Denver, CO), positioned bilaterally anterosuperior to the medial malleoli and secured with athletic tape. These IMUs recorded linear accelerations (±16g at 1,125Hz and ±200g at 1,600Hz) of the lower limbs during each training session to determine the total lower limb impact load. Impact load was calculated as the sum of all resultant accelerations related to each footfall during the practice using iMeasureU Step software (Vicon IMeasureU Step, Denver, CO) (Burland et al., 2021)

Following sensor placement, all participants completed a standardized pre-practice warm-up led by a National Strength and Conditioning Association (NSCA) certified strength and conditioning specialist, followed by sport-specific warm-up led by the coaching staff. During the basketball warm-up, participants stepped aside to complete their pre-practice CMJs. Each subject performed three CMJs in succession, with the average of the three jumps used to compute CMJ metrics. Immediately after practice, a second set of CMJs were obtained using the same standardized CMJ testing protocol as for the pre-practice, outlined below.

4.3.1: Countermovement Jump Testing Protocol

The CMJ tests were conducted using Vald ForceDecks FD4000 Dual Force Platforms (ForceDecks, London, United Kingdom) with a sampling rate of 1,000 Hz. Vald proprietary desktop software was used to verify the quality of each CMJ and define key phases of the jump. A 20N offset from the subject's pre-jump body mass defined the start of the movement. The transition from the eccentric to the concentric phase was identified at the point of minimum displacement, corresponding to a value of zero velocity. Take-off was defined as the point at which the total vertical force fell below 20N. This method has been demonstrated to provide accurate and reproducible assessments of the CMJ metrics (Heishman et al., 2020).

To ensure consistency and reliability in testing, the following steps were implemented:

a. *Participant Positioning:* Participants stood directly behind force plate, waiting for researcher's cue to step onto force plates.

b. *Participant Stands on Force Plate:* Participants stepped onto the middle of the force plate and were instructed to stand completely still with their hands on their hips.

c. *Weight Measurement:* The participants weight was automatically measured by the force plate software and was recorded for subsequent calculations.

d. *Hand Placement:* Participants were instructed to maintain their hands on their hips throughout the testing protocol.

e. *Jumping Instruction:* The cue for the CMJ was, "Jump as fast and as high as you can."

d. *CMJ Execution*: The first jump was initiated after a verbally counted three-second quiet period (e.g., "3-2-1-Jump", the participant could jump at any time past this point). Participants were instructed to return to the centre of the force plate for each subsequent jump for a brief quiet standing period before the next jump was cued.

4.4: Variables of Interest

This study examined a set of dependent variables to evaluate potential neuromuscular fatigue following on-court practice sessions, grouped into 3 distinct categories. First, **CMJ performance outcome metrics**, including *jump height* (m), *contraction time* (s), and *mRSI*, were analyzed as they represent commonly evaluated metrics in research and practical applications (Bishop et al., 2023; Claudino et al., 2017). Second, **phase-specific temporal metrics**, including *eccentric duration* (ms), *braking phase* (ms), *time to peak force* (s), and *concentric duration* (ms) were assessed. Finally, **phase-specific driver metrics**, including *peak force* (N), *mean force* (N), and *impulse* (N·s) during eccentric and concentric phases, as well as *force at zero velocity* (N) during the amortization phase, were evaluated. These CMJ metrics were calculated using Force Decks software, enhancing the broader applicability of the findings within the sport-science community.

In addition to CMJ metrics, total practice load (g's) was obtained from the wearable sensors worn during each session. This variable represented the cumulative accelerations experienced by participants, as measured by IMUs.

4.4: Statistical Analysis

A multilevel statistical approach was used to address each research question regarding acute changes in CMJ metrics. After exporting variables from the commercial software, further processing was conducted using custom Python scripts to visualize data, conduct quality checks, compute descriptive statistics, and assess normality. Shapiro-Wilk tests indicated significant deviations from normality for most metrics, suggesting non-normal distributions.

To account for the repeated measures design, as well as potential issues of normality and missing data, a mixed-effects linear model was employed(Iannaccone et al., 2021). This model tested changes in dependent variables between pre-and post-practice CMJ metrics (i.e., fixed effect of time) while controlling for repeated assessments from individual players (i.e., random effects of participants). Additionally, the mixed-effects model evaluated the effect of practice impact load on changes in CMJ metrics (i.e., fixed effect of practice volume).

Chapter 5: Results

5.1: Countermovement Jump Collections

The study included 14 male collegiate basketball athletes from McMaster University. Of these, six athletes were forwards, contributing a total of 35 pre-to-post CMJ measures, while the remaining eight athletes were guards, who contributed a total of 60 pre-to-post CMJ measures. Not all players were able to complete both pre- and post- jumps each practice. Missing data were typically due to i) minor injury obtained in practice, ii) participants not participating in practice due to injury or soreness, iii) participants leaving practice early for class. A summary of pre-test characteristics, along with addition information on missing data is presented in Table 1.

Table 2: Descriptive statistics for the measured countermovement jumps.

Position	N	Jumps	Missed Jumps	Height (cm) ± SD	Weight (kg) ± SD	Jump height (cm) ± SD	mRSI (m/s) ± SD	Impact Load (g) ± SD
Forwards	6	35	61*	198.5 ± 4.3	91.7 ± 13.1	39.8 ± 7.4	0.49 ± 0.09	86,416 ± 34,427
Guards	8	60	101*	185.6 ± 6.4	75.2 ± 7.0	39.9 ± 4.4	0.54 ± 0.09	79,787 ± 25712

*Indicates days in which an athletes completed a pre-practice jump but was unable to complete a post-practice jump

5.2: Research Question 1 – Changes in CMJ Metrics Following Practice

The first research question analyzed changes CMJ metrics following an uncontrolled practice intervention to assess their utility as markers for neuromuscular fatigue. The CMJ metrics were categorized into three groups, and changes from pre- to post-practice were examined using a mixed-effects linear model.

With respect to the CMJ **performance outcome metrics**, both jump height (Pre: 39.9 ± 5.7 cm; Post: 38.2 ± 6.6 cm; $p<0.001$) and mRSI (Pre: 0.52 ± 0.09; Post: 0.50 ± 0.11; $p<0.001$) were reduced following practice, as shown in Table 3. The overall duration of the movement (e.g., contraction time) increased slightly (Pre: 770 ± 80 ms; Post: 780 ± 81 ms; p=0.06) but was not statistically significantly.

For **phase-specific temporal metrics**, all metrics showed small increases following practice (ES: 0.10-0.28). However, only the time from movement start to peak force (p<0.01; Figure 4) and braking phase duration (p<0.001) reached significance. Further details are provided in Table 3 and Appendix A.

For **phase-specific driver metrics**, several braking-specific metrics showed significant reductions. Specifically, peak force (Pre: 1800 ± 280 N; Post: 1700 ± 260 N; p<0.001), mean force (Pre: 990 ± 150 N; Post: 960 ± 150 N; p<0.001), impulse (Pre: 56 ± 15 N·s; Post: 51 ± 13 N·s; p<0.001), and rate of force development (Pre: 5400 ± 1400 N/s; Post: 4700 ± 1500 N/s; p<0.001) all showed significant reductions.

For the **amortization phase**, force at zero velocity was significantly reduced (Pre: 76.38 ± 28.76 N; Post: 66.96 ± 30.25 N; p<0.001).

In the **concentric phase**, both mean force (Pre: 1700 ± 190 N; Post: 1600 ± 180 N; p<0.001) and impulse (Pre: 230 ± 28 N·s; Post: 220 ± 27 N·s; p<0.001) were significantly reduced. In contrast, peak force did not show a significant change (Pre: 2100 ± 270 N; Post: 2100 ± 270 N; p=0.45). See Table 3 and Appendix A for additional statistics.

Table 3: Pre-Post practice changes in CMJ force-time metrics

Metric	Pre-practice mean (SD)	Post-practice mean (SD)	p-value	Effect size
Performance Output Metrics				
Jump Height (Imp-Mom) [cm]	39.9 (5.7)	38.2 (6.6)	<0.001	-0.45
mRSI (Imp-Mom) [no units]	0.52 (0.09)	0.50 (0.11)	<0.001	-0.27
Contraction Time [ms]	770 (80)	780 (81)	0.064	0.19
Phase-Specific Temporal Metrics				
Eccentric Duration [ms]	510 (57)	520 (59)	0.074	0.19
Concentric Duration [ms]	260 (34)	260 (34)	0.166	0.10
Movement Start to Peak Force [s]	0.63 (0.11)	0.65 (0.11)	0.002	0.28
Braking Phase Duration [ms]	300 (50)	320 (53)	<0.001	0.25
Phase-Specific Driver Metrics: Eccentric				
Peak Force [N]	1800 (280)	1700 (260)	<0.001	-0.58
Mean Force [N]	990 (150)	960 (150)	<0.001	-0.61
Impulse [N·s]	56 (15)	51 (13)	<0.001	-0.52
Rate of Force Development [N/s]	5400 (1400)	4700 (1500)	<0.001	-0.49
Phase-Specific Driver Metrics: Amortization				
Force at Zero Velocity [N]	76.38 (28.76)	66.96 (30.25)	<0.001	-0.59
Phase-Specific Driver Metrics: Concentric				
Peak Force [N]	2100 (270)	2100 (270)	0.478	-0.10
Mean Force [N]	1700 (190)	1600 (180)	<0.001	-0.37
Impulse [N·s]	230 (28)	220 (27)	<0.001	-0.57

Note: p-value is from mixed-effects linear model, with effect size represented as Cohen's d for interpretation purposes.

5.3: Research Question 2 – Association with Practice Load

The second research question examined the relationship between practice volume, as measured by the IMUs, and the magnitude of change in CMJ metrics. No significant associations were observed between practice volume and changes in performance output metrics (jump height: p=0.37; mRSI: p=0.89; contraction time: p=0.12).

Similarly, no significant associations were observed practice volume and changes in any phase-specific temporal metrics, including eccentric duration (p=0.07), concentric duration (p=0.83), movement start to peak force (p=0.12), and braking phase duration (p=0.95).

In addition, no significant associations were observed for practice volume and changes in any phase-specific driver metrics across all phases: eccentric phase (peak force: p=0.35; mean braking force: p=0.30; impulse: p=0.21; braking RFD: p=0.30), amortization phase (force at zero velocity: p=0.40), or concentric phase (peak force: p=0.88; mean force: p=0.95; impulse; p=0.47). Detailed statistics surrounding the mixed-effects linear model are presented in Appendix A.

Although no significant group-level associations were identified, it is important to note that the presence of unique individual-level relationships. Figure 5 visualizes this by plotting the change in a phase-specific temporal metric (movement start to peak force) following practice relative to the practice volume experienced. In general, this figure suggests that as practice volume increases, the change in the duration of this metric also increases. However, the lack of consistency across players explains the absence of significant group-level findings.

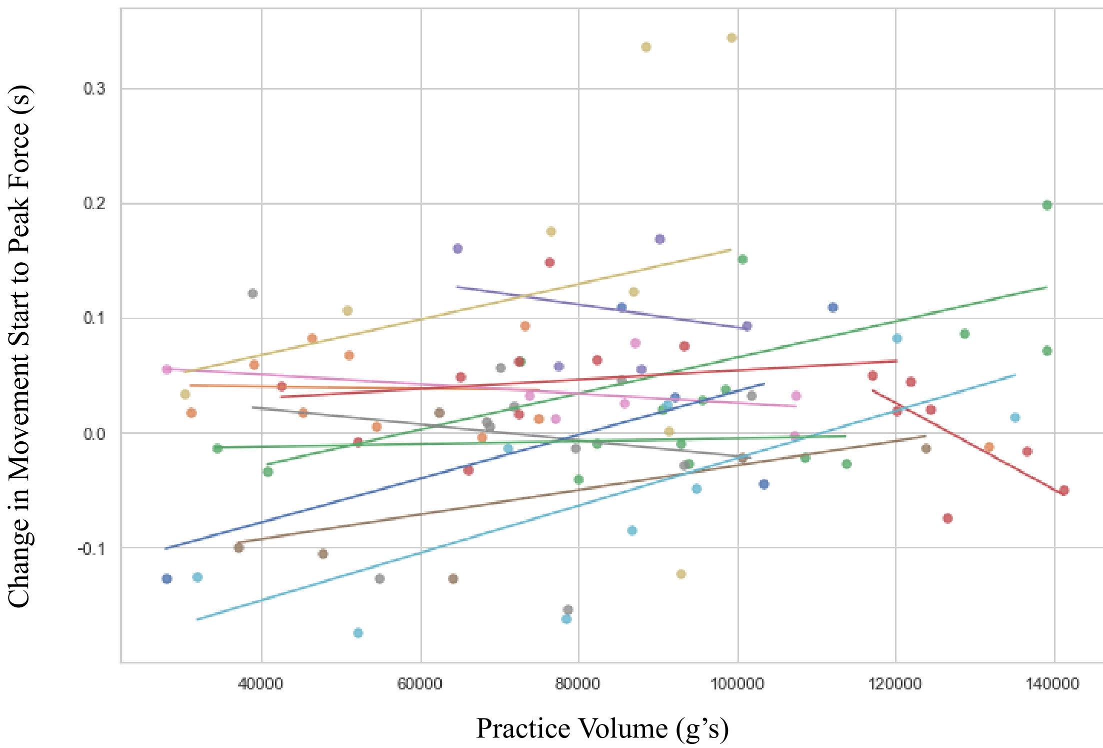


Figure 3. Individual player associations (different colour circles/lines) between the change in movement start to peak force (s) and practice volume (g's) (p=0.12).

Chapter 6: Discussion

The primary goal of this study was to evaluate the effect of practice volume on commercially generated CMJ metrics as proxies for neuromuscular fatigue. A secondary aim was to determine whether the magnitude of change in these CMJ metrics was associated with variations in practice volume. The results showed significant decreases in most CMJ metrics following a typical basketball practice, with the exception of contraction time, eccentric duration, concentric duration, and concentric peak force ($p>0.05$). Additionally, while relationships may exist at the individual player level, the magnitude of changes in these metrics was not significantly associated with training volume overall, and this result did not change when accounting for player position. Overall, these findings suggest that CMJ metrics, particularly those related to specific phases of the CMJ, are sensitive to acute fatigue following practice. However, the magnitude of these changes does not appear to be influenced by practice volume or player position.

6.1 Performance Outcome Changes

The results demonstrate that all commercially derived CMJ metrics, except for contraction time, concentric duration, eccentric duration, and concentric peak force, were significantly affected by acute practice volume. These findings both align with and diverge from those reported in previous research (Alba-Jiménez et al., 2022; Bishop et al., 2022, 2023). For instance, the current study observed significant decreases in output-based metrics, including jump height and mRSI following practice ($p<0.001$). Specifically, Cabarkapa et al. (2023) reported significant decreases in jump height (2.1cm; ES=0.31) and mRSI (0.055; ES=0.49) post practice in male collegiate basketball athletes, closely mirroring the reductions observed in this study (jump height: 1.7cm; ES=0.45; mRSI: 0.02; ES=0.27). In contrast, Gathercole et al. (2015) investigated the effects of both acute fatigue and chronic training on elite snowboard cross athletes and observed an increase in jump height (2cm increase; ES=0.47) following an acute fatigue intervention. These conflicting findings may reflect a variety of factors, such as sport-specific training demands or the nature of the fatigue induced, but ultimately highlight the potential limitations of performance output metrics like jump height alone.

Consequenty, changes in jump height may have less sensitivity as a marker of neuromuscular fatigue because athletes adjust their movement strategies in fatigued states to maintain performance (Gathercole et al., 2015). While performance outcome metrics, such as jump height and mRSI, are easy to interpret and allow for quick adjustments to training and recovery protocols, they may not fully capture the underlying changes in movement strategies driving these performance shifts. Phase-specific force-time metrics, which account for temporal and strategic adjustments, may provide deeper insights into the effects of neuromuscular fatigue, offering a more nuanced understanding of athlete readiness (Gathercole, 2014). Therefore, it is important to further explore how phase-specific force-time metrics, may be altered following the high SSC loads and fatigue of a basketball practice (Gollhofer, Komi, Miyashita, et al., 1987; Komi, 2000).

6.2 Phase Specific changes

This study revealed significant increases in temporal metrics following practice (e.g., braking phase duration) and significant decreases in driver metrics post-practice (p<0.001; Table 3). These changes likely reflect alterations in SSC function (Gollhofer, Komi, Miyashita, et al., 1987; Komi, 2000; McMahon et al., 2018). Traditional laboratory studies have shown that large volumes of submaximal SSC activities can induce performance changes, typically characterized by increased contact times and reduce mechanical efficiency (Komi, 2000; Nicol et al., 2006). Findings by Kennedy and Drake et al. support this idea, suggesting that altered movement strategies, such as prolonged contraction times, often compensate for reduced eccentric function caused by SSC fatigue.

These results align somewhat with prior literature on phase-specific temporal metrics. For example, Cabarkapa et al. (2023) reported a significant increase in the contraction time (23ms increase; ES=0.33), while the current study found a smaller but similar trend (10ms increase; ES=0.19; p=0.07). Other temporal metrics exhibited similar patterns, including movement start to peak force (20ms increase; ES=0.28; p=0.002) and braking phase duration (20ms increase; ES=0.25; p<0.001). These findings suggest potential changes in movement strategy in response to acute fatigue, likely driven by a less efficient SSC. When a CMJ is performed over a longer period of time, stored energy may dissipate, leading to reduced movement efficiency (Claudino et al., 2017). Additionally, slower movements may fail to elicit a meaningful stretch reflex, an essential SSC mechanism, further contributing to performance decrements (Claudino et al., 2017).

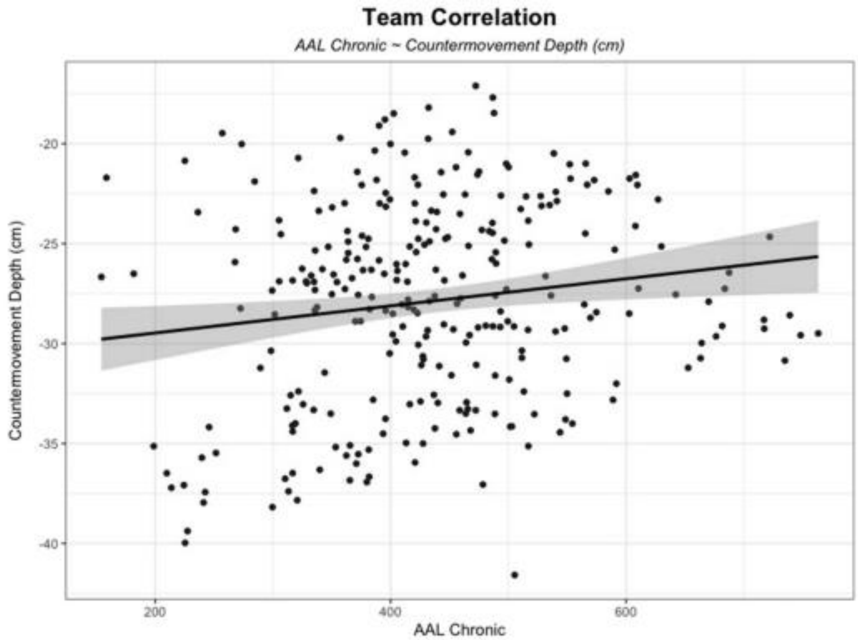
Beyond temporal metrics, some of the largest changes observed in this study were observed in eccentric force metrics, including peak force, mean force, impulse, and rate of force development, all of which showed moderate decreases. This is consistent with the expectation that a fatigued state results in a less efficient countermovement phase (Claudino et al., 2017). However, these findings contrast with Cabarkapa et al., (2023) who found trivial changes in these eccentric force-based metrics. The reason for this discrepancy is unclear, as both studies employed similar methodological protocols and technology (ForceDecks Max, VALD Performance, Brisbane, Australia). A notable difference, however, was the verbal cueing used during jump protocols. This work used the cue, “jump as high and as fast as you can” while Cabarkapa et al. instructed athletes to focus on “pushing the ground as explosively as possible”. Differences in cueing may influence jump execution and, consequently, underlying force-time metrics (Xu et al., 2024).

Taken together, these results suggest that while the phase-specific metric most sensitive to fatigue may vary between studies, the utility of phase-specific force-time metrics over performance output metrics remains consistent. This aligns with Yu et al. (2020), who observed significant changes in lower limb kinematics and kinetics after a running-induced fatigue protocol, particularly in joint angles and moments during the push-off and landing phases. These findings emphasize the importance of monitoring a comprehensive range of force-time metrics to assess the effects of fatigue and practice on athletic performance. By leveraging these additional metrics, practitioners can make more informed adjustments to training and recovery strategies, developing precise interventions to address specific aspects of neuromuscular fatigue and performance adaptation.

6.3: Relationship to Practice Volume

Although force plate metrics were sensitive to acute changes, the magnitude of these changes was not significantly associated with practice volume. This finding aligns with those of Ellis et al., who monitored CMJ performance and training volume in a cohort of youth male soccer players. Ellis and colleagues observed consistent changes in force-time components due to acute fatigue but found no evidence of a dose-response relationship between training volume and force plate metrics (Ellis et al., 2022). In contrast, Philipp et al. (2023) reported a significant association between CMJ depth and practice volume (p=0.02) in female collegiate basketball players(Philipp et al., 2024). While this may initially appear contradictory to the current results, a closer examination of the data from Philipp et al. reveals similar trends. Figure 4, from their study, shows a small group-level relationship (Figure 4A), but also highlights substantial variability in individual player responses (Figure 4B). These findings suggest that while relationships between phase-specific CMJ metrics and practice volume may exist, the strength and direction of these associations are highly variable across players.

A.



B.

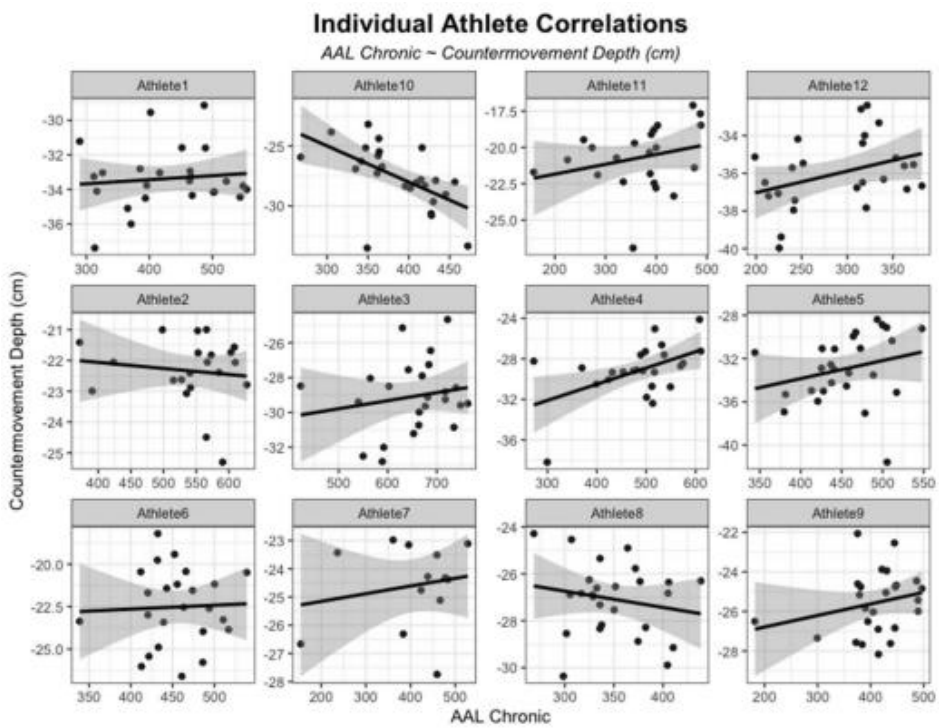


Figure 4. Figures from Philipp et al. (2024) showing A) team level associations between practice volume (Accumulated Acceleration Load; AAL Chronic) and countermovement depth, as well as B) individual level relationships.

These results indicate that although force plate metrics effectively detect acute fatigue, the observed changes are not consistently related to practice volume or training load across players. This lack of a clear dose-response relationship may stem from individual variability in fatigue responses. Factors such as training history, fitness level, recovery strategies, and day-to-day or chronic fatigue effects likely influence how athletes respond to training loads. This variability can confound the impact of training load on CMJ performance, potentially contributing to a bimodal response to neuromuscular fatigue (Heishman, Daub, Miller, Freitas, & Bemben, 2020; Nicol et al., 2006; Spiteri et al., 2014). Future research should prioritize understanding these individual differences and developing personalized monitoring protocols. Such approaches may enable practitioners to better tailor training and recovery programs, accounting for the nuanced and highly individualized nature of fatigue responses.

6.4: Study Limitations

This study has several limitations that should be acknowledged. First, a substantial number of post-practices CMJ tests were missed by players, primarily due to minor injuries or soreness sustained during practice. While requiring these players to complete the tests could have raised ethical and practical concerns, this likely biased the results toward players who were less affected by practice volume. As a result, the observed changes following practice, and their association with practice volume, may have been limited. Second, this study did not include game data, where higher intensities and workloads may elicit greater changes in CMJ metrics compared to practice sessions. Incorporating game data in future studies could provide a more comprehensive understanding of the relationship between workload and neuromuscular fatigue. Finally, the sample size was limited to a single team, which reduced the statistical power of the analyses. Future research should consider including multiple teams or conducting more detailed individual-level analyses, especially given the observed variability in individual adaptations to practice volume.

Conclusion

This study demonstrates the significant impact of basketball practice on various force-plate metrics, including decreases in output-based metrics such as jump height and RSI-Modified, and increases in phase-specific temporal metrics like braking phase duration. These findings align with previous research and highlight the role of stretch-shortening cycle (SSC) fatigue in altering neuromuscular performance. While output metrics are valuable for their simplicity and practical application, phase-specific force-time metrics provide deeper insights into movement adaptations and fatigue, enabling more targeted training and recovery strategies. However, no significant relationships were found between practice volume and the magnitude of changes in these metrics, suggesting individual variability in fatigue responses. The findings underscore the importance of robust monitoring systems that incorporate multiple metrics sensitive to neuromuscular fatigue. Future research should aim to validate these metrics across larger cohorts and explore personalized monitoring approaches to optimize training programs and manage fatigue.

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APPENDIX

Table A1: Relationship between practice volume and the magnitude of change in force plate metrics.

Metric	Parameter	Estimate	P-value
Performance Output Metrics			
Jump Height (Imp-Mom)	Position	1.58	0.20
	Practice Volume	0.00	0.37
	Practice Volume x Practice	0.00	0.19
RSI-modified (Imp-Mom)	Position	0.02	0.77
	Practice Volume	0.00	0.89
	Practice Volume x Practice	0.00	0.72
Contraction Time	Position	57.16	0.19
	Practice Volume	0.00	0.12
	Practice Volume x Practice	0.00	0.19
Phase-Specific: Temporal			
Eccentric Duration	Position	47.21	0.17
	Practice Volume	0.00	0.07
	Practice Volume x Practice	0.00	0.13
Concentric Duration	Position	9.17	0.46
	Practice Volume	0.00	0.83
	Practice Volume x Practice	0.00	0.76
Movement Start to Peak Force	Position	-0.01	0.86
	Practice Volume	0.00	0.12
	Practice Volume x Practice	0.00	0.97
Braking Phase Duration	Position	3.20	0.88
	Practice Volume	0.00	0.95
	Practice Volume x Practice	0.00	0.90

Table A2: Relationship between practice volume and the magnitude of change in force plate metrics.

Metric	Parameter	Estimate	P-value
Phase-Specific Driver - Eccentric			
Eccentric Peak Force	Position	52.92	0.67
	Practice Volume	0.00	0.35
	Practice Volume x Practice	0.00	0.80
Eccentric Mean Braking Force	Position	-3.54	0.91
	Practice Volume	0.00	0.30
	Practice Volume x Practice	0.00	0.78
Eccentric Braking Impulse	Position	-0.61	0.91
	Practice Volume	0.00	0.21
	Practice Volume x Practice	0.00	0.68
Eccentric Braking RFD	Position	-116.59	0.89
	Practice Volume	-0.01	0.30
	Practice Volume x Practice	0.00	0.91
Phase-Specific Driver - Amortization			
Force at Zero Velocity	Position	60.19	0.63
	Practice Volume	0.00	0.40
	Practice Volume x Practice	0.00	0.76
Phase-Specific Driver - Concentric			
Concentric Impulse	Position	13.58	0.20
	Practice Volume	0.00	0.47
	Practice Volume x Practice	0.00	0.29
Concentric Peak Force	Position	-42.80	0.57
	Practice Volume	0.00	0.88
	Practice Volume x Practice	0.00	0.56
Concentric Mean Force	Position	11.61	0.85
	Practice Volume	0.00	0.95
	Practice Volume x Practice	0.00	0.81