COUNTERMOVMENT JUMP ASSESSMENT FOR MONITORING PROLONGED

FATIGUE IN COLLEGIATE FEMALE SOCCER PLAYERS

by
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ABSTRACT

Introduction: Females are 4 to 6 times more likely to sustain an anterior cruciate ligament (ACL) injury than their male counterparts during running and cutting sports, such as soccer. This sex disparity is thought to result from altered lower limb neuromuscular control that females present when fatigued at the end of practice or games. Yet, current fatigue monitoring techniques typically vary in their reliability, applicability and efficiency. **Purpose:** The purpose of this study is to test the feasibility of the countermovement jump (CMJ) to quickly and reliably monitor fatigue in female soccer athletes. **Methods:** Twenty-two (age: 19.3 ± 1.1 yrs, ht: 1.7 ± 7.2 m, and wt: 61.9 ± 7.7 kg) females from an NCAA Division I soccer team had peak isokinetic strength and power and specific ground reaction metrics of a CMJ including: peak and rate of force/power development, impulse, and reactive strength index modified, quantified immediately before off-season training, and immediately prior to- and following the completion of the competitive season. **Results:** Quadriceps and hamstrings peak torque and average power increased following the competitive season for both limbs compared to pre-season and pre-training time points (all: $p < 0.05$). During the CMJ, maximum rate of power production and peak force were greater at the post-season compared to pre-training ($p = 0.023$ and $p = 0.007$, respectively) and pre-season ($p = 0.024$ and $p = 0.044$, respectively) time points, while peak power was greater at post-season compared to the pre-training ($p = 0.018$) time point. Changes in relative net impulse, peak power, peak landing force, and jump height during the CMJ demonstrated moderate to strong relations to changes in isokinetic variables from pre-training to post-season (all: $p < 0.05$, $r > 0.4$). Lastly, the same CMJ measures accurately identified 96% of starters (Eigenvalue = 2.147, $p = 0.038$) and 86% of first-year athletes, although the classification of first-year athletes was not statistically different than non-first-year athletes (Eigenvalue = 1.279, $p = 0.173$). **Conclusion:** The current research identifies the CMJ task as a promising tool for athletic trainers and sports performance coaches to reliably monitor female soccer performance in general, and training loads specifically. Immediately following the competitive season, the current athletes increased isokinetic strength and power as well as CMJ performance, with changes in CMJ performance exhibiting a significant relation to changes in isokinetic strength and power. Yet, following off-season training, where isokinetic strength and power declined, albeit insignificantly, a similar relation between changes in CMJ performance and isokinetic strength and power was not observed. The experimental outcomes may indicate that the CMJ task is better suited for identifying increases in strength and power rather than decrements and fatigue. These same CMJ measures may serve as an effective tool for identifying improved strength and power, and performance differences for specific members of a collegiate soccer team, as 96% of starters and 86% of first-year athletes were accurately identified.

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LIST OF ABBREVIATIONS

CMJ	Countermovement Jump
vGRF	Vertical Ground Reaction Force
PF	Peak CMJ Force
MRFD	Maximal Rate of Force Production
PP	Peak CMJ Power
MRPD	Maximal Rate of Power Production
RSI	Reactive Strength Index
JH	Jump Height
LPF	Landing Peak Force
RNI	Relative Net Impulse
BW	Body Weight
ES	Effect Size (Cohen's d)

CHAPTER ONE: INTRODUCTION

Anterior cruciate ligament (ACL) rupture is a common, costly musculoskeletal injury which disproportionately affects female athletes. Females, in fact, are reportedly 4 to 6 times more likely to suffer an ACL injury during running and cutting sports, such as soccer, than their male counterparts[5]. Considering female participation in competitive collegiate soccer has increased approximately 1,500% since the early 1980's, there has been a substantial increase in the number of ACL injuries suffered by young, and otherwise healthy, active athletes[2]. Although, such injuries only accounted for 0.7% of the approximately 55,000 reported injuries between 2004 and 2009 for female NCAA soccer players[3], their impact on the individual and team is substantial. Each ACL injury has a significant physical, mental, and monetary cost that places a substantial burden on the student athlete. [5,6,7] Direct treatment and rehabilitation costs are estimated at $25,000 per ACL injury[5], and result in significant time away from sport[3], negative psychological and physiological changes[6], reduced academic performance[6], and up to 90% greater risk for early onset arthritis[7,44]. As such, it is imperative researchers provide athletic trainers and sports performance coaches the ability to successfully monitor and minimize ACL injury risk for all female athletes, but particularly those that participate in running and cutting sports, such as soccer.

Upwards of 70% of ACL injuries occur from a non-contact mechanism, where the athlete herself, with no direct external contact to knee, applies the forces that rupture the ligament[5,6,8,9,10,11,41]. But, non-contact ACL injuries are difficult to monitor and prevent as risk is multifactorial. Hewett et al.[5] reported over 30 extrinsic risk factors for non-contact ACL injury, including anatomical, hormonal, biomechanical, and neuromuscular factors. Neuromuscular control is a risk factor that plays an important role in non-contact injury[6,10], as it exhibits a sex dimorphism[16-20] and may be modifiable through training[45-47]. Sex differences in neuromuscular control become evident following puberty[13,14,15], which coincides with the emergence of the sex disparity in non-contact ACL injury rate[42]. Following puberty, females exhibit altered neuromuscular control during sports-relevant movements (e.g., jumping, landing and cutting) compared to males[16,17,18,19,20]. Specifically, females exhibit altered muscular activation and strength of the quadriceps and hamstrings[16,20] that lead to altered biomechanics, including reduced hip and knee flexion[17] and increased knee abduction angle[19] and moments[18], thought to decrease joint stability and increase ACL loading and injury risk during sports-relevant movements[20]. Targeted neuromuscular training reportedly reduces females ACL injury risk by increasing active knee joint stabilization[45,46]. Yet, despite training improvements, reductions in the sex disparity for ACL injury rate in general, or female non-contact ACL injury risk specifically have yet to be documented[47].

Fatigue purportedly alters neuromuscular control in trained[30] and untrained[43] female athletes, potentially increasing non-contact ACL injury risk. Specifically, fatigue, or failure by the athlete to produce and/or maintain required muscular forces (or power) , leads to potentially hazardous alterations in neuromuscular control towards the end of practice or late in games when injuries typically occur [2,21,43]. Fatigue-altered neuromuscular control reportedly leads to increased ACL loading through greater knee abduction[22], proximal anterior tibial shear[22], increased ground reaction forces[23], and decreased knee flexion angle[22] during sports-related movements. Additionally, fatigue has shown to impair general knee flexor/extensor strength[30] and balance[40], which are reported to further reduce joint stability during sports-related movements[5]. Fatigue; however, is multifaceted. Athletes experience both acute[22] (short-term) and cumulative[33] (prolonged or chronic) fatigue. Numerous studies have examined the effect of acute fatigue on athlete performance and injury risk[38,39], yet little is known regarding the cumulative effects of fatigue. Recently, McLean et al. reported starters on a NCAA Division I Women's soccer team demonstrate significant decrements in muscular power following their competitive season compared to non-starters[33]. However, McLean's use of an inertial cycling test may be less applicable to athletic teams due to the required specialized equipment, time, and financial costs. Additionally, first-year collegiate (i.e., freshman) athletes have a greater injury rate than their more experienced teammates, and may accumulate more fatigue as they adjust to new and increased demands of the elevated competitive level[31,32]. As such, athletic trainers and/or sports performance coaches have an immediate need to identify and manage athlete workloads. Providing this capability will lead to improved physical performance and reduce the number of injuries that occur towards the end of practice, late in games, or in the second half of competitive seasons for both starters and first-year athletes[34].

The overarching objective of this study was to test the feasibility of the countermovement jump (CMJ) to quickly and reliably monitor fatigue in female soccer athletes. Specifically, this study sought to determine whether researchers can detect acute and cumulative fatigue using a CMJ for both starters and first year athletes on a Division

I Women's soccer team immediately following their off-season training and competitive season.

Specific Aims

Specific Aim 1

To quantify fatigue of NCAA Division I female soccer athletes. Specifically, this study quantified fatigue through reductions in peak knee flexor and extensor torque and power during concentric isokinetic (60 °/second) contractions immediately prior to offseason training, along with immediately prior to- and following completion of a competitive season for Division I soccer athletes.

Hypothesis 1.1

All athletes will exhibit significant decreases in peak knee flexor and extensor power and strength immediately following, but not immediately prior-to offseason training, when compared to pre-training.

Hypothesis 1.2

Starters will exhibit significant decreases in peak knee flexor and extensor power and strength compared to non-starters immediately following the competitive season, but not immediately following offseason training.

Significance

Quantifying the cumulative fatigue that occurs following a competitive collegiate soccer season will provide trainers and coaches with an understanding of athlete responses to training to better manage athlete workloads and improve physical performance and reduce injury risk over the course of the season.

Specific Aim 2

To evaluate fatigue of NCAA Division I Women's soccer athletes using a countermovement jump. Specifically, this study will quantify specific ground reaction force parameters, including peak and rate of force and power development, reactive strength index (RSI modified), and relative impulse exhibited during maximal CMJs performed immediately following off-season training, and determine whether it relates to decrements exhibited in peak isokinetic power at the same time points.

Hypothesis 2.1

Immediately following off-season training, athletes will exhibit a significant reduction in RSI modified and rate of development/peak force and power during take-off of the CMJ, and significant increase in peak force and net impulse during landing of the countermovement jump, when compared to pre-training.

Hypothesis 2.2

Takeoff and landing variables quantified during maximal CMJs performed immediately following off-season training will exhibit a significant relation to peak isokinetic power quantified during concentric isokinetic (60 °/second) contractions performed at the same time point.

Significance

Collegiate athletic trainers and sports performance coaches currently lack an easy, reliable, and affordable method for quantifying cumulative fatigue. Providing ground reaction force metrics, which can be quickly and easily obtained from a CMJ, will provide collegiate trainers and coaches the reliable and affordable method necessary to monitor athlete fatigue and reduce their injury risk.

Specific Aim 3

To determine whether the countermovement jump can identify cumulative fatigue exhibited by starters and/or first year Division 1 soccer athletes. Specifically, this study will quantify rate of force and power development, peak force and power, and RSI modified during the take-off phase, in addition to peak force and impulse recorded during the landing phase of maximal CMJs performed by starters and first-year athletes immediately following their off-season training and competitive season.

Hypothesis 3.1

Following the competitive season, starters will exhibit significantly greater reductions in takeoff, (peak and rate of force and power development, and RSI modified) ground reaction force measures and increases in landing (peak force and impulse) ground reaction measures during the CMJ as compared to non-starters.

Hypothesis 3.2

Following offseason training, first-year athletes will exhibit significantly greater reductions in takeoff (peak and rate of force and power development, and RSI modified) ground reaction force measures and increases in landing (peak force and impulse) ground reaction measures during the CMJ as compared to non-first-year athletes.

Significance

The cumulative fatigue of a collegiate soccer season or off-season training program may lead to altered and potentially hazardous neuromuscular control that increases injury risk during practice or competitive games. However, collegiate trainers and coaches currently lack a reliable, repeatable, and efficient method to evaluate this fatigue. Knowledge from this study can be used by athletic trainers and sports performance coaches to easily and affordably monitor athlete’s off- and in-season workloads, providing them an avenue to reduce the incidence of ACL injury.

CHAPTER TWO: LITERATURE REVIEW

The following will examine literature to help identify the need for a novel technique in monitoring cumulative fatigue in collegiate female soccer players. Specifically, this will detail 1) injury incidence and cost of anterior cruciate ligament (ACL) injuries, 2) risk factors and mechanisms for ACL injury, 3) impact of fatigue and soccer specific fatigue, 4) current fatigue monitoring techniques.

Injury Incidence/Cost

In the sport of soccer (football) anterior cruciate ligament (ACL) injuries reportedly occur within a wide range between 0.06 to 3.7 injuries per 1000 hours of athlete exposures[4,8]. As one of the most popular sports worldwide with an estimated 256 million active players as of 2006[1], the seemingly low incidence rate for ACL injury results in a large number of cases each year based on shear number of players alone. While this type of injury is not exclusive to females there is a disproportionate number of injuries when comparing statistics of male and female injury rates. Studies examining this gender discrepancy have found a wide range of differences from approximately 3 times greater rate of injuries to females[9] to as high as 13 times greater[1]. In either case it is clear that females are more likely to sustain such an injury compared to their male counterparts. From data obtained for NCAA Women's soccer (all divisions), which included 27,811 participants in 2018[2], overall injury rate was determined to be 7.3 per 1,000 athlete exposures from data obtained from the 2004/2005 through 2008/2009 seasons. This rate was substantially higher during competitive games compared to practice (14.4 per 1,000 exposures compared to 5.0 per 1,000 exposures)[3]. While only accounting for a small percentage (0.7%) of the total injuries, anterior cruciate ligament (ACL) injuries resulted in the most substantial amount of lost time, a median of 159 activity time loss days[3]. In addition to the loss of time attributed to these injuries there is a substantial financial burden of an estimated range of $17,000-$25,000 for surgery and rehabilitation per injury[5]. Taking 0.7% of the total 55,000 injuries over the course of the NCAA study would indicate that 385 such injuries occurred over the time frame. Using the low-end cost estimate per injury this results in a total cost of $6,545,000 over the 4-year period or an average of $1,636,250 per year. These estimates also fail to include other consequences attributed to ACL injury including scholarship cost[6], psychological and physiological changes[6], academic performance[6], and increased risk for early onset arthritis[7]. Further data regarding the timing of injuries non-specific to ACL found that injury rates were highest during the pre-season (9.8 per 1,000 exposures), followed by the regular season (6.8 per 1,000 exposures), and lastly the post season (3.8 per 1,000 exposures)[2]. Further, a greater number of injuries were sustained during the second half (51.2%) compared to the first half (32.9%) of competitions[2]. Non-specific to soccer, studies on injury rates in collegiate swimming[31] and gymnastics[32] were greatest in first-year eligible (freshman) athletes.

Risk Factors and Injury Mechanism

Due to the immense financial, physiological, and psychological toll resulting from ACL injury there is a considerable amount of published research pertaining to identifying risk factors, mechanisms, and prevention strategies to injury. The result of this research has been inconclusive in finding a direct answer; however, one recurring theme has concluded that the majority of ACL injuries result from a non-contact (no direct contact with knee) injury mechanism[11,12]. While results of specific studies may vary there is a consensus that approximately 70% of ACL injuries result from a non-contact event[5,6,8,9,10,11,12]. An extensive review of risk factors and injury mechanisms surrounding non-contact ACL injuries compiled greater than 30 such mechanisms/factors including, but not limited to: Extrinsic (bracing, shoe-to surface interaction); Anatomical (increased Q angle, femoral notch width, joint laxity, muscular flexibility, body mass index (BMI)); Hormonal (effects of estrogen and oral contraceptives); Neuromuscular (antagonist-agonist relationships, magnitude and timing of muscle activation, decreased proprioception); Biomechanical (sagittal/coronal/transverse plane movements of the hip, knee, and ankle); and finally prior injury[5,10,11,12]. While not exhaustive, the factors outlined above serve to demonstrate the multifactorial nature of such injury and the difficulty in identifying at-risk athletes. While altered neuromuscular control can be attributed to injury across age and gender, sex differences in neuromuscular control become more distinct following puberty[13,14,15]. This finding may account for the discrepancy in injury rates also becoming apparent following maturity[42]. As compared to males, mature females exhibit reduced quadriceps and hamstring strength[16], greater quadriceps to hamstring strength ratios[16]; reduced hip and knee flexion[17], increased external knee abduction moments[18], and increased knee valgus angle[19] during landing, and altered muscular activation of the hamstrings and quads including increased quadriceps activation[20], reduced hamstring-to-quadriceps co-activation ratio (H/Q-ratio)[20], and lateral quadriceps (vastus lateralis) dominance[20]. These gender differences noted are all suggested to lead to increased ACL injury risk through greater ACL loading or reduced joint stability[20]. While it has been shown that targeted neuromuscular training has the ability to reduce many of these factors and subsequent injury risk[6] and possibly reduce discrepancies in neuromuscular control of males and females[6], the onset of fatigue has been suggested negatively influence neuromuscular control[5,43] even in highly trained athletes[30,37].

Fatigue and Biomechanics

While fatigue may not be directly related to ACL injury itself, it has been demonstrated to play a role in reducing optimal neuromuscular control factors which influence ACL injury[5]. Fatigue is a multifaceted concept which can vary based on the context for which it is viewed. The definition proposed by Edward[21] that fatigue is a "failure to maintain the required or expected force (or power output)" serves as a practical definition for fatigue experienced by soccer athletes. Fatigue inducing protocols have shown the influence on neuromuscular control[21-25], including a 14% decrease in knee flexion angle and a 21% increase in peak proximal tibial anterior shear force for all genders during a stop-jump task following a protocol to simulate fatigue found in sports such as soccer[22]. In addition, a gender effect was noted as females displayed a mean increase in mean valgus moment of 96% while on average the males displayed a knee varus moment[22]. This finding was repeated using a drop-jump task which also found significant increases in peak vertical ground reaction force, peak rectus femoris activity, and peak foot abduction regardless of sex[23]. Further, proprioception and balance have shown to be impaired following fatigue[24,25], with research into young (mean age of 14.5 years) elite soccer players exhibiting increases in sway measurements for both bipedal and unipedal stances after fatigued[40].

Soccer-Specific Fatigue

Elite level soccer players demonstrate a decline in exercise intensity in the second half of competitions which may suggest fatigue[27]. In addition, reductions in performance can be seen following periods of high-intensity exercise during a match and towards the end of a match indicating that fatigue occurs both during and at the end of the match[29]. Over 40% of top-class male soccer players experienced their least intense exercise period in the final 15 minutes of the game, with similar findings in top-class female players as well[27]. Countermovement jump (CMJ) performance and markers of muscle damage and inflammation, such as creatine kinase activity, cortisol, and testosterone, have shown decrements which are maintained over 48 hours post-match[28] In observing females between 2 matches, 72 hours apart, significant decrements to sprint performance, CMJ performance, and isokinetic strength were found following the first match[30]. Sprint performance returned to baseline 5 hours post-match, followed by peak torque during knee extension (27 hours post) and knee flexion (51 hours post), however CMJ performance had not returned to baseline over the course of the study[30]. While less research has looked into the cumulative fatigue effect over the course of a season, one such study observed significant reductions in maximal power output of starters on a collegiate female soccer team during the second half of a season, while maximal power output in non-starters was maintained, indicating a lasting fatigue effect from games and highlighting need for monitoring of training load over the course of a season[33].

Fatigue Monitoring Techniques

There are a number of proposed methods in monitoring fatigue which can be broken down into three main approaches: observational, physiological, and subjective[34]. Many of the methods used for each approach were outlined in the 2009 review from Borresen and Lambert[35]. These were further broken into techniques of monitoring internal load: the physiological and psychological stress imposed on the athlete, and external load: the work completed, capability, and capacities for the athlete[36]. Among others, monitoring techniques for internal load include rating of perceived exertion (RPE), heart rate, training impulse (TRIMP), lactate concentrations, and other biochemical, hormonal, and immunological assessments such as creatine kinase activity[36]. While internal load may play a significant role in fatigue of an athlete[36], of specific interest to this study is the monitoring of external loads, specifically regarding neuromuscular function. As discussed previously, altered neuromuscular function as a result of fatigue has potential in increasing athletic injury risk. Potential markers for external load monitoring include average peak height achieved during CMJ, reactive strength index (RSI) during multiple rebound jump tests (MRJ), and mean sprint time during a 20-m linear sprint[37]. In an effort to determine the validity of each of these tests, and including a squat-jump test, Gathercole and colleagues examined each using a 3-day baseline testing, followed by a multifaceted fatiguing protocol, with follow up tests at 0-hours, 24-hours, and 72-hours post-fatigue[38]. From this, it was concluded that “the high repeatability and fatigue sensitivity of the CMJ test indicated it to be the most valid test for neuromuscular fatigue detection in this investigation”[38]. CMJ variables which are highly reproducible include max rate of power and force development, peak force and power, ratio of flight time to contraction time, and relative net impulse[26]. While many CMJ variables have shown to be affected immediately following the fatigue protocol[39], decrements in the aforementioned variables have shown to maintained up to 72 hours post-exercise indicating a greater time of recovery for such variables[26]. Finally, when determining the optimal strategy for assessing CMJ performance and fatigue the average of jump results, rather than results.

CHAPTER THREE: MANUSCRIPT

Introduction

Anterior cruciate ligament (ACL) rupture is a costly musculoskeletal injury that is 4 to 6 times more likely for females compared to male athletes in running and cutting sports, such as soccer[5]. Female participation in competitive collegiate soccer has increased approximately 1,500% since the early 1980's[2], leading to a substantial increase in the number of ACL injuries suffered by young, and otherwise healthy, active athletes. Each ACL injury has a significant physical, mental, and monetary cost[5,6,7] that substantially burdens the injured athlete. Direct treatment and rehabilitation costs are estimated at $25,000 per ACL injury[5] and result in significant time away from sport[3], negative psychological and physiological changes[6], reduced academic performance[6], and up to 90% greater risk for early onset arthritis[7,44]. As such, it is imperative researchers provide athletic trainers and sports performance coaches the ability to successfully monitor and minimize ACL injury risk for all female athletes, but particularly those that participate in running and cutting sports.

Upwards of 70% of ACL injuries occur from a non-contact mechanism, where the athlete, with no direct external contact to knee, applies the forces that rupture the ligament[5,6,8,9,10,11,41]. But, non-contact ACL injuries are difficult to monitor and prevent as risk is multifactorial. Hewett et al.[5] reported over 30 extrinsic risk factors for non-contact ACL injury, including anatomical, hormonal, biomechanical, and neuromuscular factors. Neuromuscular control is a risk factor that plays an important role in non-contact injury[6,10], as it exhibits a sex dimorphism[16-20] and may be modifiable through training[45-47]. Sex differences in neuromuscular control become evident following puberty[13,14,15], which coincides with the emergence of the sex disparity in non-contact ACL injury rate[42]. Following puberty females exhibit altered neuromuscular control during sports-relevant movements (e.g., jumping, landing and cutting) compared to males[16,17,18,19,20]. Specifically, females exhibit altered muscular activation and strength of the quadriceps and hamstrings[16,20] that lead to altered biomechanics, including reduced hip and knee flexion[17] and increased knee abduction angle[19] and moments[18], thought to decrease joint stability, and increase ACL loading and injury risk during sports-relevant movements[20]. Targeted neuromuscular training reportedly reduces females ACL injury risk by increasing active knee joint stabilization[45,46]. Yet, despite training improvements, reductions in the sex disparity for ACL injury rate in general, or female non-contact ACL injury risk specifically, have yet to be documented[47].

Fatigue purportedly alters neuromuscular control in trained[30] and untrained[43] female athletes, potentially increasing non-contact ACL injury risk. Specifically, fatigue, or failure by the athlete to produce and/or maintain required muscular forces (or power) [21], leads to potentially hazardous alterations in neuromuscular control towards the end of practice or late in games when injuries typically occur [2,43]. Fatigue-altered neuromuscular control reportedly leads to increased ACL loading through greater knee abduction[22], proximal anterior tibial shear[22], increased ground reaction forces[23], and decreased knee flexion angle[22] during sports-related movements. Additionally, fatigue has been shown to impair general knee flexor/extensor strength[30] and balance[40], which are reported to further reduce joint stability during sports-related movements[5].

Fatigue, however, is a multifaceted. Athletes experience both acute[22] (short-term) and cumulative[33] (prolonged or chronic) fatigue. Numerous studies have examined the effect of acute fatigue on athlete performance and injury risk[38,39], yet little is known regarding the cumulative effects of fatigue. Recently, McLean et al. reported starters on a NCAA Division I Women's soccer team demonstrate significant decrements in muscular power following their competitive season compared to non-starters[33]. However, McLean's use of an inertial cycling test may be less applicable to athletic teams due to the required specialized equipment, time, and financial costs. Additionally, first-year collegiate (i.e., freshman) athletes have greater injury rate than their more experienced teammates[31,32], as they adjust to new and increased demands of the elevated level of competition. As such, collegiate athletic trainers and/or sports performance coaches have an immediate need to identify and manage athlete workloads. Providing this capability will provide a means to improve physical performance[34] and reduce the number of injuries that occur towards the end of practice, late in games, or in the second half of competitive seasons for both starters and first-year athletes.

The overarching objective of this study was to test the feasibility of the countermovement jump (CMJ) to quickly and reliably monitor fatigue in female soccer athletes. Specifically, this study looked to detect acute and cumulative fatigue using a CMJ for both starters and first year athletes on a Division I Women's soccer team immediately following their off-season training and competitive season. We hypothesized that due to accumulated fatigue starters would demonstrate a significant reduction in isokinetic and CMJ muscular strength and power following the competitive season compared to non-starters; while freshman athletes would demonstrate similar fatigue-induced significant reductions in muscular strength and power following off-season training compared to non-freshman. Additionally, we hypothesized that specific CMJ muscular strength and power variables would relate to changes in isokinetic muscular strength and power following off-season training and competitive season and could successfully discriminate between starters and non-starters as well as freshman and non-freshman.

Methods

Participants

Twenty-two females (age: 19.3 ± 1.1 yrs, ht: 1.7 ± 7.2 m, and wt: 61.9 ± 7.7 kg) from a NCAA Division I soccer team participated. Each participant had to be between 18 and 24 years of age and in good physical health to be included. Potential participants were excluded if they had: 1) recent injury and/or pain in the back or lower extremity, 2) recent surgery in the back or lower extremity, 3) known neurological disorder, or 4) were currently pregnant. Prior to testing, research approval by the Institutional Review Board (IRB) was obtained and each participant provided written consent.

Experimental Design

Each participant completed three test sessions. During each test session, participants had knee flexor and extensor strength data measured and recorded while also performing a battery of sports-relevant tasks. The test order for isokinetic and sports-relevant tasks was determined for each participant using a random number generator (either 0 or 1), with 0 equal to isokinetic testing, prior to the beginning of each testing. The three test sessions were completed: (1) immediately prior to off-season training (Pre-training), (2) immediately following completion of off-season training (Pre-season), and

(3) immediately following completion of the competitive season (Post-season) (see Appendix B for further training details). Upon completion of the competitive season, coaches provided information related to participant year of eligibility (freshman, sophomore, etc.), the number of minutes played, and the number of games started for each participant.Starters were defined as those participants which started greater than or equal to 50% of games and played greater than or equal to 50% of the total minutes for the season. Freshman athletes were defined as those participants in their first year of eligibility.

Biomechanical Test Sessions

Upon arrival of the first testing session, participant consent was obtained as well as and limb dominance recorded. Limb dominance was identified at the leg each participant prefers to kick a ball[52]. Following this, and at the of the pre-season and post-season test session, participants had anthropometric data (height, weight, age and leg length). Leg length was measured as the distance between the head of the greater trochanter and the center of the lateral malleolus for the dominant limb and recorded in centimeters (to nearest 0.5cm) with a standard cloth measuring tape.

During each test session, participants' knee flexor and extensor strength and power were recorded via an isokinetic dynamometer (Humac Norm, Computer Sports Medicine Inc., Stoughton, Massachusetts, USA) and they completed a series of sports-related tasks over two in-ground force platforms (AMTI OR6 Series, Advanced Mechanical Technology, Inc., Watertown, Massachusetts, USA). To record knee flexor and extensor strength, participants performed five concentric/concentric isokinetic (60 °/second) contractions with each limb (dominant vs. non-dominant)[48]. For each contraction, the dynamometer was set-up according to manufacturer specifications. Participants were seated with approximately 110 degrees of hip flexion and the involved limb stabilized using restraints to isolate the targeted muscle groups[53]. The axis of rotation of the knee joint was aligned with the mechanical rotation axis of the dynamometer for each subject[48] with the shin cuff of the lever arm restrained approximately 1 inch proximal to the medial malleolus[53]. Knee range of motion was identified per subject to obtain maximal values of extension and flexion for the movement. First, each participant performed 5-repetition warm up at a self-selected effort level followed by a 1-minute rest. Then, participants performed 5 maximal repetitions of concentric knee extension and flexion, starting with knee extension. During testing, participants were given visual feedback of their strength and verbal encouragement. Average power (Watts) and peak torque (N*m) from the "best" repetition was recorded for flexion and extension of each limb. The muscular strength and power measures were normalized to participant bodyweight (kg) for comparison across the participant group. Test order for each limb was randomized using a random number generator (either 0 or 1), with 0 equal to the dominant limb.

Participants also completed a series of sports-related tasks during each test session, which included: countermovement jump (CMJ), drop vertical jump (DVJ), bilateral single-leg cut, and dynamic balance. The testing order of each task was randomized using a 6 x 6 Latin Square prior to testing (**Table 3.1**). For the purpose of this study, only the CMJ was analyzed. For the CMJ, participants began in an athletic position, with feet shoulder width apart and parallel on the two in-ground force platforms. Then, the participant performed a countermovement squat immediately before a maximal vertical jump. Each participant was required to complete five “good” CMJ trials[49]. A CMJ was considered “good” if the participant began the jump with a sufficient countermovement, took-off and landed with one foot on each specified force plate. During each jump, vertical ground reaction force (vGRF) data was recorded at 2400 Hz and stored in Vicon Nexus (v2.3, Vicon Motion Systems Ltd., Oxford, UK) for post-processing.

Table 3. 1 The Latin Square Design used for randomization of the testing order for each task and subject

	Order 1	Order 2	Order 3	Order 4	Order 5	Order 6
Task 1	DVJ	Rt. Cut	Lt. Cut	CMJ	Lt. Balance	Rt. Balance
Task 2	Rt. Balance	CMJ	Rt. Cut	Lt. Balance	DVJ	Lt. Cut
Task 3	Rt. Cut	Rt. Balance	Lt. Balance	Lt. Cut	CMJ	DVJ
Task 4	CMJ	Lt. Cut	DVJ	Rt. Balance	Rt. Cut	Lt. Balance
Task 5	Lt. Cut	Lt. Balance	CMJ	DVJ	Rt. Balance	Rt. Cut
Task 6	Lt. Balance	DVJ	Rt. Balance	Rt. Cut	Lt. Cut	CMJ

Biomechanical Analyses

The vGRF data from each CMJ was processed using a custom Python script (v3.6, Python Software Foundation, Wilmington, Delaware, USA). First, GRF data was low-pass filtered using a fourth-order Butterworth filter (12 Hz) and smoothed using a rolling mean with a window of 5. The start of the CMJ was defined as the first instance vGRF droped below a threshold of 2.5% bodyweight[54] (**Fig. 3.1**). Takeoff and landing were identified as the first instance that vGRF fell below or exceededs 5 N, respectively (**Fig. 3.1**). Additionally, the contraction phase was defined as start of CMJ to take-off, and the landing phase defined as landing to peak vGRF following landing.

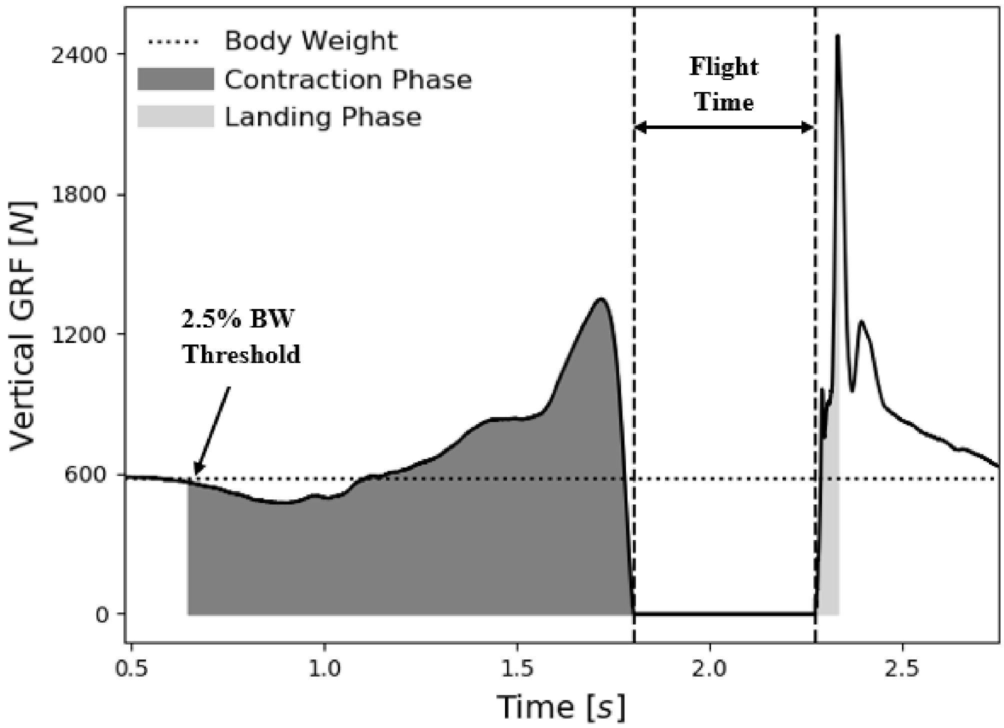

Figure 3. 1 Typical vGRF during CMJ with target thresholds and jump phases identified

During the CMJ, specific GRF metrics were calculated during both contraction and landing phases. Specifically, during the contraction phase, peak vGRF (N)[26], peak power (W)[26], maximum rate of force (N/s) and power (W/s) production[50], reactive strength index (RSI) modified, and jump height (JH) were calculated. Peak vGRF and power were obtained from the maximum values of the respective measures during the contraction phase. To obtain power, vGRF was multiplied by velocity (**Eq. 1**).

$$P(t) = vGRF(t) * v(t) \tag{1}$$

To calculate velocity, vGRF bodyweight removed (**Eq. 2**) was divided by participant mass to calculate acceleration (**Eq. 3**) then integrated over the contraction phase (**Eq. 4**).

$$rGRF(t) = vGRF(t) - mg \tag{2}$$

$$a(t) = \frac{rGRF(t)}{m} \tag{3}$$

$$v(t) = \sum_{t_{start}}^{t_{takeoff}} a(t)\Delta t, \qquad initial = 0 \tag{4}$$

Rate of force (**Eq. 5**) and power (**Eq. 6**) production were expressed as the maximum change in the respective variables over a 10ms window during the contraction phase.

$$RFD(t) = \frac{vGRF(t+0.01) - vGRF(t)}{0.01} \tag{5}$$

$$RPD(t) = \frac{P(t+0.01) - P(t)}{0.01} \tag{6}$$

RSI modified (**Eq. 7**) was obtained by dividing flight time (measured by time from takeoff to landing) by ground contact time (measured from jump start to takeoff) and presented as a ratio[26].

$$RSI = \frac{Flight\ Time}{Contraction\ Time} \tag{7}$$

During the landing phase, landing peak vGRF (N), and relative net impulse (J) were calculated. Total impulse was obtained by multiplying peak vGRF by the time of the landing phase in seconds[51],

$$I = vGRF_{peak} * (t_{peak} - t_{land}) \tag{8}$$

All GRF metrics, excluding RSI modified, were then normalized to bodyweight for comparison across the participants.

Statistical Analysis

Independent samples t-tests of participant-based means for group demographics were used to identify significant differences in age, height, weight, playing time and games started between groups. The dependent variables submitted to analysis were quadriceps and hamstrings average power and peak torque for both dominant and non-dominant limb, and lower body peak vGRF, peak power, maximum rate of force and power production, JH, and RSI modified during the contraction phase and landing peak vGRF (LPF) and relative net impulse (RNI) during the landing of the CMJ task. Each dependent GRF variable was averaged over the “good” 5 trials to create a participant-based mean. Then, each participant-based mean was submitted to repeated measures ANOVA to test the main effect and interaction between group (freshman/non-freshman or starter/non-starter) and time (pre-training, pre-season, post-season). Significant interactions were submitted to simple effects analysis, and a Bonferroni correction was used for pairwise comparisons[55]. Effect size (ES) was calculated for each significant pairwise using Cohen’s d[60]. Additionally, an absolute change of all dependent variables was calculated following training (pre-season – pre-training) and the competitive season (post-season – pre-season), and then multiple stepwise linear regression were fit to determine which CMJ variables predicted changes in muscular strength and/or power. For each step, independent variables were retained in the final equation if $p < 0.05$, while a significance of $p > 0.10$ was used to exclude variables from each stepwise model. Finally, discriminant analyses[56] were used to determine if group membership (freshman/non-freshman or starter/non-starter) could be identified by CMJ performance. All statistical analysis was performed using SPSS (v25.0, IBM Corporation, Armonk, New York, USA), with alpha set a priori $p < 0.05$.

Results

Participant Demographics

Starters were significantly older ($p = 0.028$), played more minutes ($p < 0.001$), and started more games ($p < 0.001$), but did not differ in height or weight ($p > 0.05$) from non-starters (**Table 3.2**). Freshman were significantly younger ($p > 0.001$) but did not differ in height or weight ($p > 0.05$) from non-freshman (**Table 3.3**).

Table 3. 2 Demographics for Starters versus Non-Starters

	Age (yr)	Height (cm)	Weight (kg)	Games Started	Minutes Played
Starter	19.89 (1.05)	169.33 (6.12)	65.01 (7.09)	22.22 (1.20)	1788.11 (169.84)
Non-Starter	18.85 (0.99)	164.32 (7.43)	59.75 (7.63)	0.69 (1.03)	304.23 (196.80)
p-value	0.028	0.111	0.117	> 0.001	> 0.001

Table 3. 3 Demographics for Freshman versus Non-freshman

	Age (yr)	Height (cm)	Weight (kg)
Freshman	18.0 (0.0)	165.83 (9.94)	61.75 (8.65)
Non-Freshman	19.87 (0.83)	166.62 (5.98)	61.98 (7.55)
p-value	> 0.001	0.816	0.952

Isokinetic Strength and Power

There was a significant effect of time and limb for all isokinetic quadriceps and hamstring strength and power variables ($p < 0.05$) (**Table 3.4 and Table 3.5**). For both limbs, average quadriceps power and peak torque were greater at the post-season compared to pre-training (Dom: $p < 0.001$ ES = 1.216, $p < 0.001$ ES = 0.60 and Non: $p < 0.001$ ES = 0.906, $p < 0.001$ ES = 0.319) and pre-season time points (Dom: $p = 0.028$ ES = 0.214, $p = 0.003$ ES = 0.416 and Non: $p = 0.019$ ES = 0.372, $p = 0.022$ ES = 0.435). But no differences were evident between pre-training and pre-season time points ($p > 0.05$). Average hamstrings power and peak torque were greater at the post-season compared to pre-training (Dom: $p < 0.001$ ES = 1.026, $p < 0.001$ ES = 1.376 and Non: $p < 0.001$ ES = 1.026, $p < 0.001$ ES = 0.875) and pre-season time points (Dom: $p < 0.001$ ES = 0.311, $p < 0.001$ ES = 0.543 and Non: $p = 0.003$ ES = 0.416, $p < 0.001$ ES = 0.683) for both limbs, while peak hamstring torque was smaller at the pre-season compared to the pre-training time point ($p = 0.022$) for the non-dominant limb. The dominant limb exhibited greater average quadriceps and hamstrings power ($p < 0.001$, $p = 0.040$) and peak torque ($p < 0.001$, $p = 0.005$) than the non-dominant limb. There was no significant effect of group on any isokinetic variable ($p > 0.05$).

Table 3. 4 Dominant limb strength variables by time point

	Peak Torque (Nm/BW)		Average Power (W/BW)	
	Ham	**Quad**	**Ham**	**Quad**
Pre-Training	0.622 ± 0.107	0.957 ± 0.206	0.471 ± 0.095	0.553 ± 0.135
Pre-Season	0.550 ± 0.122	0.846 ± 0.245	0.438 ± 0.102	0.518 ± 0.170
Post-Season	0.801 ± 0.130*	1.101 ± 0.226*	0.619 ± 0.103*	0.773 ± 0.161*

***Denotes significant difference from pre-training and pre-season (p<0.05)**

Table 3. 5 Non-Dominant limb strength variables by time point

	Peak Torque (Nm/BW)		Average Power (W/BW)	
	Ham	**Quad**	**Ham**	**Quad**
Pre-Training	0.614 ± 0.099	0.904 ± 0.254	0.470 ± 0.084	0.531 ± 0.152
Pre-Season	0.544 ± 0.122#	0.796 ± 0.243	0.439 ± 0.107	0.486 ± 0.143
Post-Season	0.716 ± 0.102*	0.960 ± 0.216*	0.560 ± 0.092*	0.661 ± 0.143*

***Denotes significant difference from pre-training and pre-season (p<0.05)**

#Denotes significant difference from pre-training and post-season

CMJ Variables

A significant time by group interaction was observed for JH (p = 0.006) (**Fig. 3.2**). Freshman jumped significantly higher than non-freshman at the post-season time point (p = 0.019, ES = 0.981). Freshman increased jump height in the post-season compared to the pre-training (p = 0.008, ES = 0.981) and pre-season (p = 0.007, ES = 0.905) time points, while non-freshman exhibited no difference in jump height between any time point (p > 0.605).

A significant time by group interaction was observed for peak force (p = 0.039) (**Fig. 3.3**). Starters increased peak force production at the post-season compared to pre-training (p < 0.001, ES = 1.421) and pre-season (p < 0.001, ES = 1.405) time points, while non-starters exhibited no significant change in peak force production between any time point (p > 0.415).

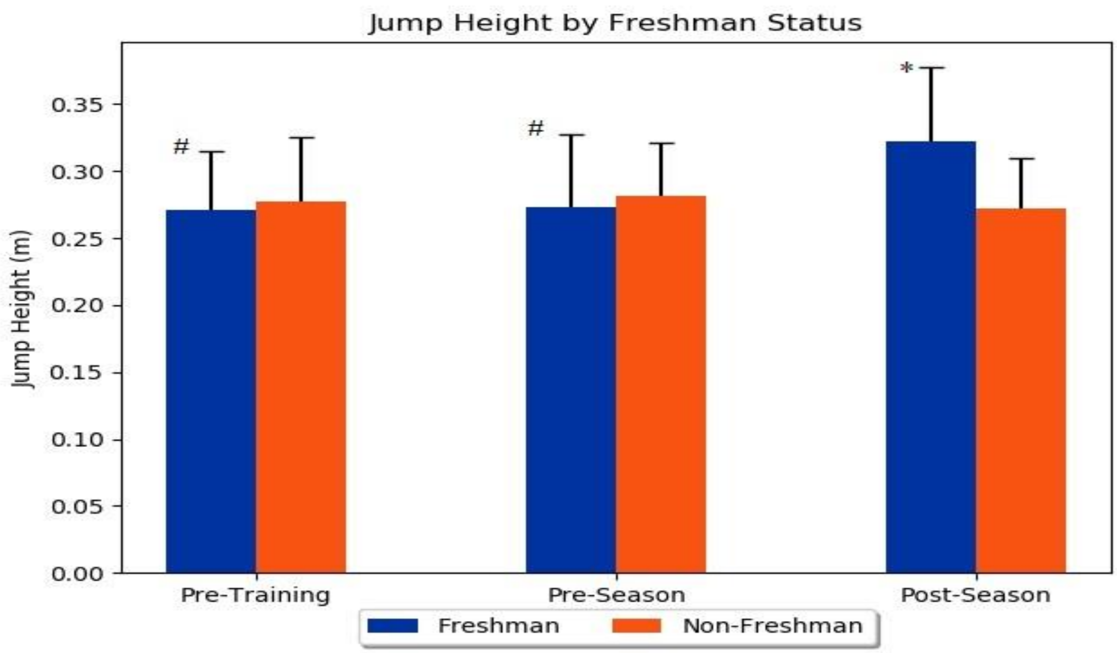

Figure 3. 2 CMJ jump height by freshman status
***Denotes significant difference from non-freshman (p<0.05)**
#Denotes significant difference from post-season

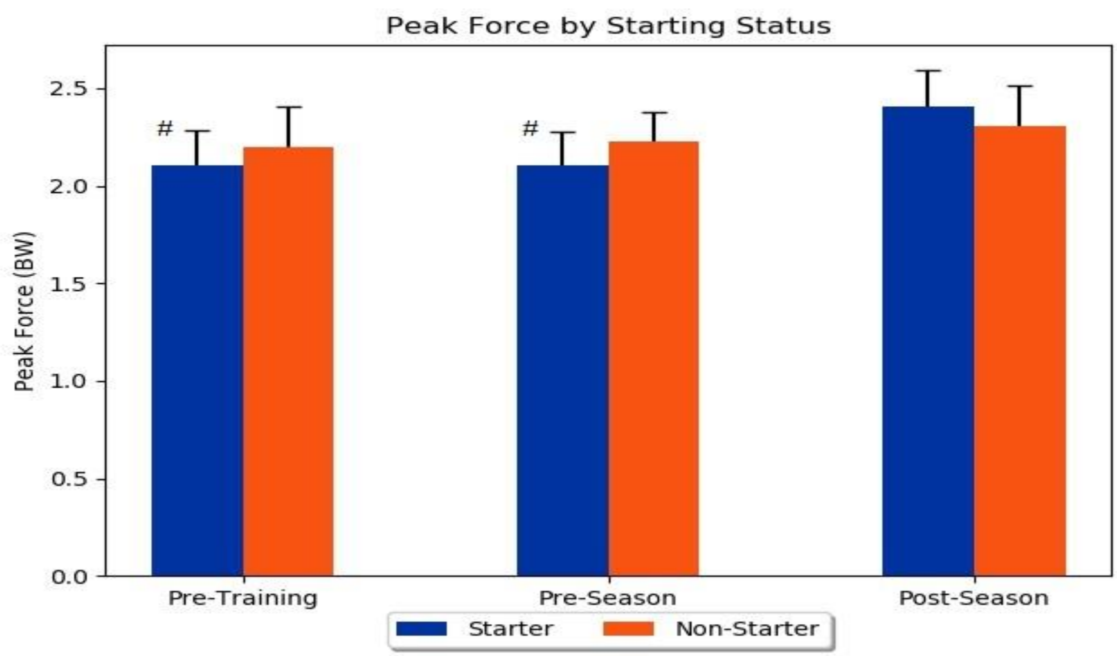

Figure 3. 3 CMJ peak force by starting status
#Denotes significant difference from post-season

A significant effect of time was evident for peak power (p = 0.025), MRPD (p = 0.027), and peak force (p = 0.009) (Table 3.6). Specifically, MRPD and peak force were greater at the post-season compared to pre-training (p = 0.023, ES = 0.699 and p = 0.007, ES = 0.827) and pre-season (p = 0.024, ES = 0.729 and p = 0.044, ES = 0.731) time points, while peak power was greater at post-season compared to the pre-training (p = 0.018, ES = 0.6) time point. No significant effect of time was observed for MRFD (p = 0.264), RSI (p = 0.056), JH (p = 0.081), LPF (p = 0.984), relative net impulse (p = 0.368), or asymmetry (p = 0.116) (**Table 3.6**). There was no significant effect of group for any CMJ variables (p > 0.05) (**Table A.1, A.2**).

Table 3. 6 Average CMJ measures by time point.

	Pre-Training	Pre-Season	Post-Season
Peak Power	4.52 ± 0.66	4.57 ± 0.57	4.80 ± 0.60#
MRPD	31.76 ± 7.62	31.57 ± 6.49	36.79 ± 7.56*
Peak Force	2.17 ± 0.20	2.19 ± 0.17	2.34 ± 0.20*
MRFD	10.25 ± 2.66	9.76 ± 2.73	11.87 ± 3.90
RSI	0.57 ± 0.19	0.48 ± 0.07	0.62 ± 0.35
JH	0.28 ± 0.05	0.28 ± 0.04	0.29 ± 0.05
LPF	3.44 ± 0.65	3.43 ± 0.55	3.42 ± 0.52
RNI	0.25 ± 0.04	0.26 ± 0.03	0.24 ± 0.02
Asymmetry	-0.52 ± 2.36	0.16 ± 3.13	0.14 ± 4.59

***Denotes significant difference from pre-training and pre-season (p<0.05)**

#Denotes significant difference from pre-training

<u>Regression</u>

Relative net impulse of the CMJ was found to be a significant predictor of the change in peak hamstring torque of the non-dominant limb following off-season training (r = 0.426, *b* = -0.978 and p = 0.048) (**Fig. 3.4**). When comparing data from pre-season to post-season, numerous significant, moderate to strong, correlations were identified. Peak CMJ power exhibited a significant relation with the change in dominant limb quadriceps average power following the competitive season (r = 0.483, *b* = 0.246 and p = 0.031) (**Fig. 3.5**), while peak force of the CMJ landing (LPF) was a significant predictor of the change in average power (r = 0.489, *b* = -0.180 and p = 0.029) (**Fig. 3.6**) and peak torque (r = 0.473, *b* = -0.218 and p = 0.035) (**Fig. 3.7**) of the non-dominant limb's quadriceps following the competitive season. Finally, CMJ JH was significant predictor of the change in average power (r = 0.447, *b* = -0.917 and p = 0.048) (**Fig. 3.8**) and peak torque (r = 0.544, *b* = -0.995 and p = 0.013) (**Fig. 3.9**) for the hamstring of the non-dominant limb.

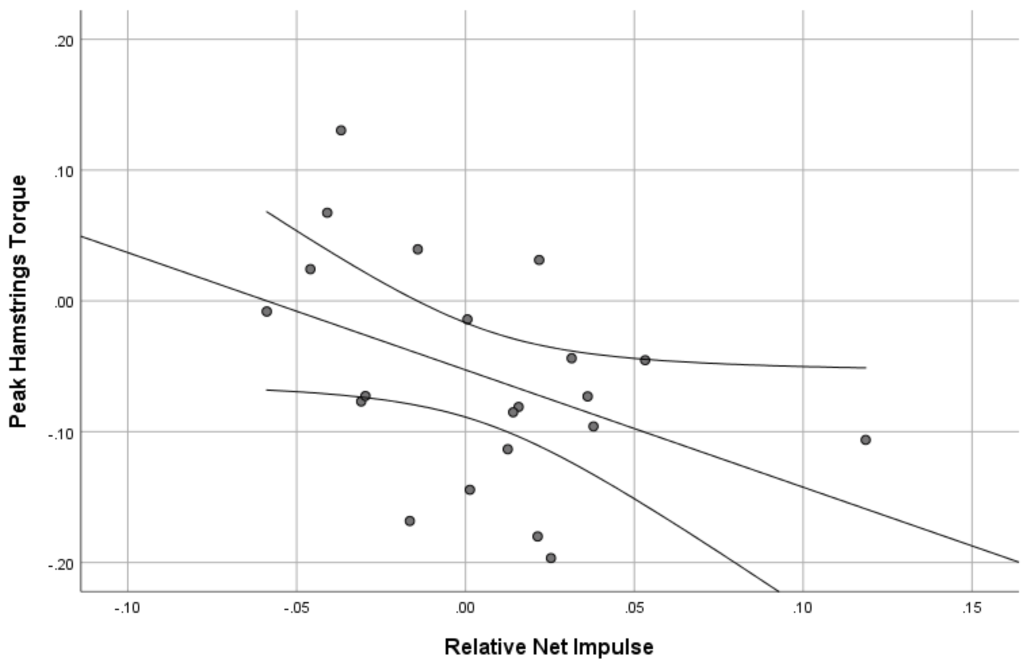

Figure 3. 4 Change in peak hamstrings torque by change in RNI

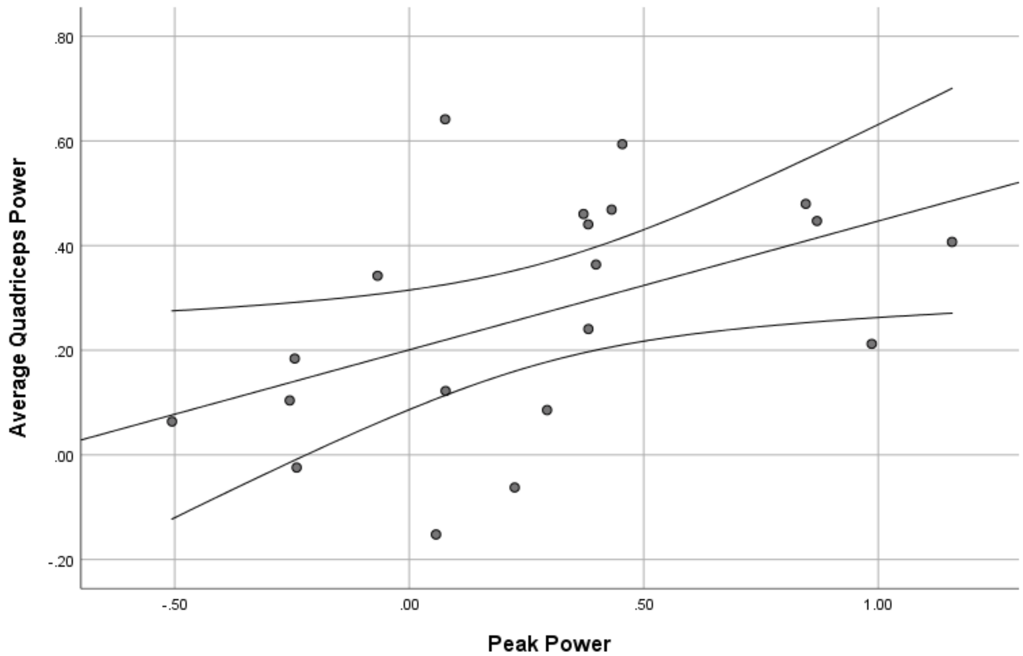

Figure 3. 5 Change in average quadriceps power by change in peak power

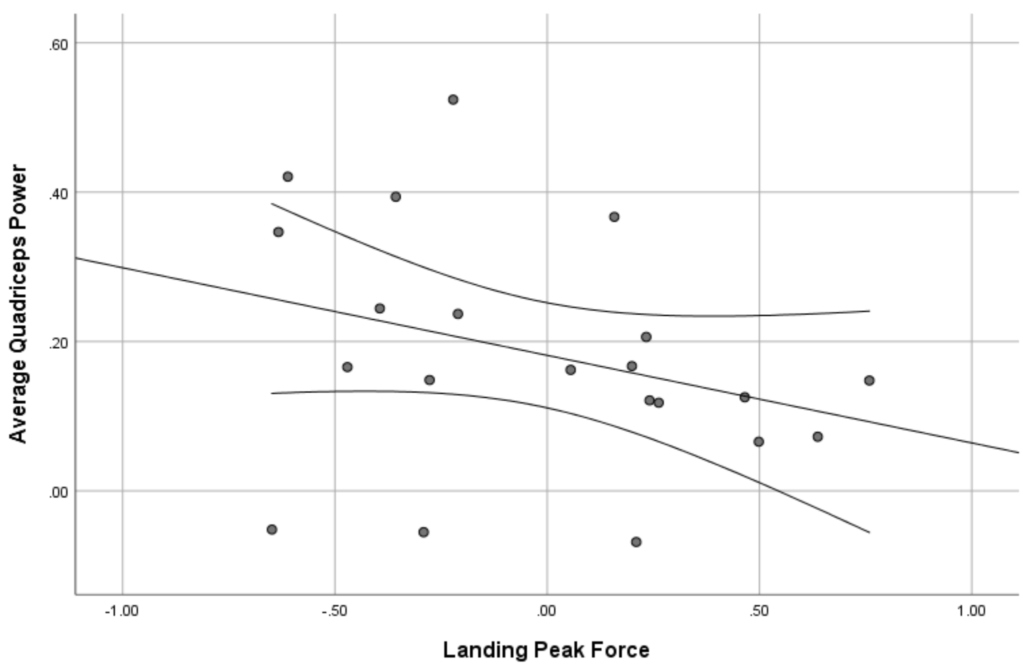

Figure 3. 6 Change in average quadriceps power by change in LPF

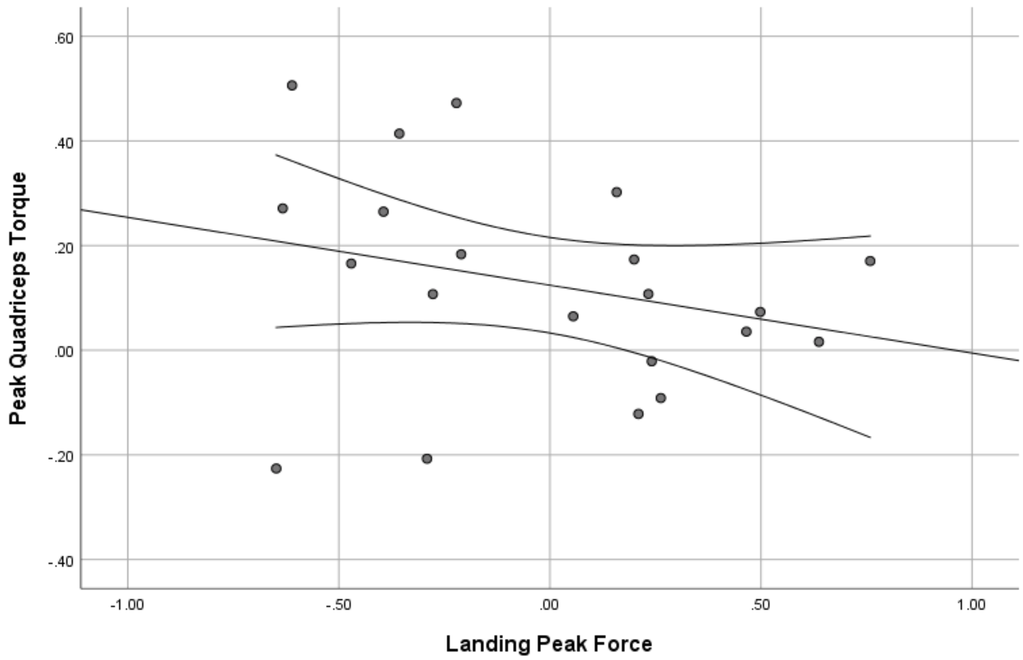

Figure 3. 7 Change in peak quadriceps torque by change in LPF

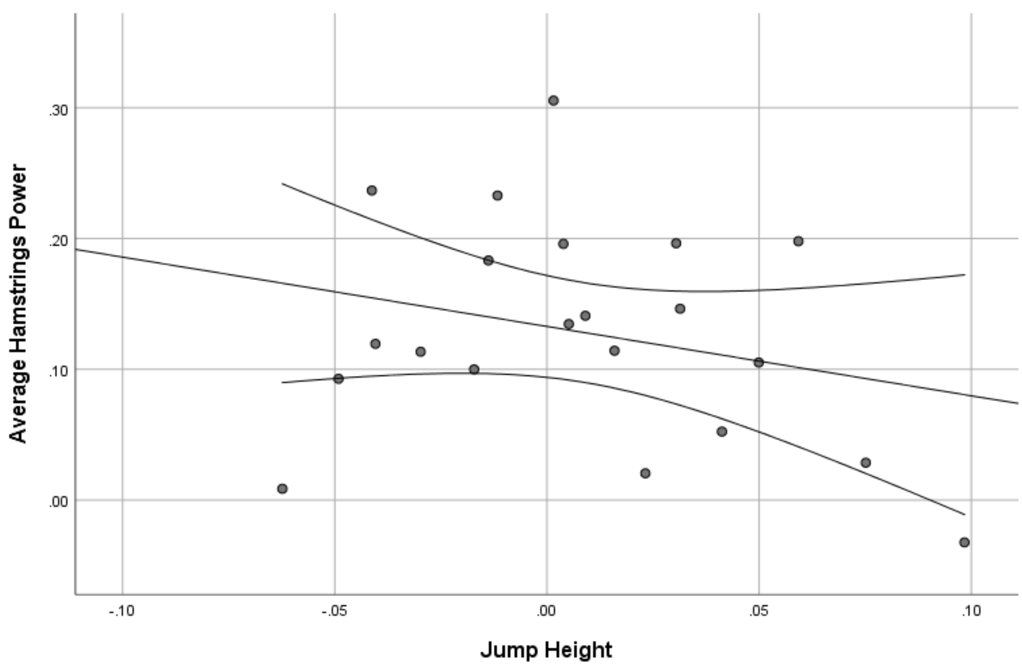

Figure 3. 8 Change in average hamstrings power by change in JH

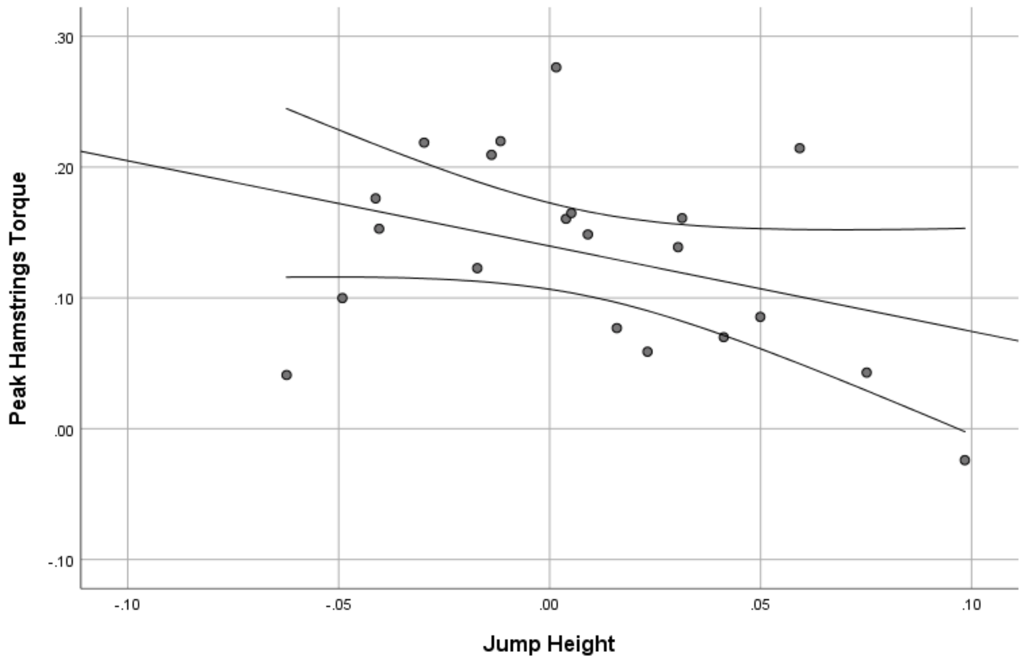

Figure 3. 9 Change in peak hamstrings torque by change in JH

<u>Discriminant Analysis</u>

All 13 non-starters and 8 of 9 starters (95.5%, Eigenvalue = 2.147) were correctly classified by the change in CMJ variables following the season. In fact, the CMJ variables were significantly different between starters and non-starters (p = 0.038) with only 31.8% of the difference between groups not explained by CMJ variables. For the second group, the CMJ variables correctly classified 5 of 7 freshman and 14 of 15 non-freshman (86.4%, Eigenvalue = 1.279). However, CMJ variables were not significantly different between freshman and non-freshman (p = 0.173) and 43.9% of the differences between groups was not explained by CMJ variables.

Discussion

To combat the deleterious effects of fatigue, this study sought to determine whether athletic and sports performance coaches could quickly and reliably monitor decrements in force or power exhibited following both off-season training and a competitive season using measures of CMJ performance, and whether those CMJ measures could accurately predict starters or first-year athletes. Our hypotheses were only partially supported, as athletes exhibited significant increases in strength and power following the competitive season and insignificant decrease following training. CMJ performance measures exhibited moderate to strong relation to increases in isokinetic strength and power after the competitive season, but limited relation to decreases in strength and power following training. Although there were minimal differences in performance between the starter and first-year groups (starters increased CMJ peak force and first-year increased jump height after the season), starters could be successfully be predicted from CMJ performance; whereas first-year athletes CMJ performance was not significantly different than non-first-year athletes even though they were identified with 86% accuracy.

Strength and CMJ

In contradiction with our hypotheses, the current athletes exhibited insignificant decreases in isokinetic strength and power following offseason training, and significant increases in strength and power following the competitive season. Specifically, the soccer athletes currently tested increased isokinetic quadriceps and hamstrings strength and power between 14% and 33% for the dominant limb and between 6% and 22% for the non-dominant limb following the competitive season. Fatigue, as would be expected immediately following the competitive soccer season, reportedly reduces an athlete's ability to produce maximal strength and/or power[21]. These fatigue-related decreases in strength and power typically translate to similar reduction in physical performance[27]. Considering the current athletes increased CMJ height by 4%, and CMJ strength and power measures up to 18% (specifically a 8% to 9% increase in peak force and power, and 17% to 18% increases in rate of force and power production respectively) following the competitive season, they may not have exhibited the anticipated fatigue. These findings contradict Gathercole and colleagues, who reported a general reduction in CMJ performance following fatigue[26,38,] and Kraemer et al. who reported an approximate 14% reduction in jump height specifically[57]. While the reason for the current discrepancy is not immediately evident, it may result from differences in athlete fatigue or training methodologies. Gathercole et al. implemented a protocol that elicited acute fatigue[26] rather than the prolonged fatigue from training or competitive season currently tested. Further, the current athletes followed a consistent training routine that purposely incorporated active recovery, while the specific training methodology for Kraemer et al.'s participants is unclear, and they may not have purposely incorporated active recovery or a consistent training routine[57]. Regardless, the results herein suggest the current athletic trainers and sports performance coaches provided sufficient management of athlete training loads over the course of training and the season.

The CMJ measures exhibited promise as a quick and reliable tool to monitor muscular strength and power in collegiate female soccer athletes[33]. Specifically, the current CMJ measures, including peak landing force and power, and jump height, recorded with a force platform exhibited moderate ($r > 0.3$)[58,59] to strong ($r > 0.5$)[58,59] linear relation with changes in isokinetic strength and power following the competitive season. A 10% increase in peak CMJ landing force predicted a 0.022 Nm/kg and 0.018 W/kg reduction in peak torque and average power, while a 10% increase in jump height was associated with a 0.01 Nm/kg and 0.092 W/kg reduction in non-dominant hamstrings torque and average power respectively. Moreover, a 10% increase in peak CMJ power was associated with a 0.025 W/kg increase in average quadriceps power of the dominant limb. Further considering the moderate to strong relationship between the measured CMJ performance and isokinetic strength and power, the use of a force plate to quickly and reliability monitor decrements in female soccer athlete performance demonstrates initial promise and warrants further study.

In agreement with our hypothesis, the tested athletes decreased strength between 5%-12% following the off-season training, but only the 12% reduction in peak hamstrings torque for the non-dominant limb was statistically significant. Considering these decrements can be indicative of fatigue[21], they may result in injurious movement patterns and reduced neuromuscular control, including increased quadriceps to hamstrings strength ratios as shown by the significant reduction in hamstrings strength[5,21-25]. The resulting changes may contribute to the increased number of injuries typically seen during the pre-season training that tends to immediately follow off-season training[2]. Yet, contrary to our hypothesis, the CMJ test may not reliably identify decrements in strength and power following off-season training. Although the current athletes exhibited decrements, albeit mostly insignificant, in isokinetic strength and power following off-season training, similar decreases in CMJ performance over this period were not quantified. Specifically, changes in CMJ force and power typically ranged from a decrease of 5% (MRFD) to an increase of 2% (Peak Power) from the pre-season time point. The RSI measure, however, exhibited a decrement of approximately 13% following off-season training. Considering RSI reportedly exhibits greater sensitivity to fatigue than the other CMJ measures currently tested[26], further study is warranted to determine whether it can be used to reliably monitor decrements in athlete performance following strenuous off-season training. Further considering the effect size currently observed for the insignificant decrease in isokinetic and CMJ strength and power, testing a larger number of athletes may be necessary to identify significant decrements in specific strength and power variables following strenuous off-season training.

The CMJ force and power measures recorded following off-season training exhibited limited relation to the changes in isokinetic strength and power. Following off-season training, only RNI quantified during the CMJ exhibited a relation with changes in peak hamstring torque of the non-dominant limb, with a 10% increase in RNI associated with a 0.0978 Nm/kg reduction in non-dominant peak hamstring torque. Considering the CMJ measures demonstrated potential to predict increases in isokinetic strength and power, but limited ability to detect decreases in strength and power, more research is needed to determine the capability of CMJ measures to reliability quantify fatigue-related decrements performance.

Starter vs. Non-Starter

Starters reportedly exhibit decrements in physical performance at the completion of a competitive season. For instance, both McLean et al. and Kraemer et al. noted significant decrements in muscular power[33] and CMJ jump height[57] for starters compared to non-starters following a collegiate soccer competitive season. In agreement with these experimental outcomes, starters exhibited a significant difference in physical performance following the completion of the competitive soccer season compared to non-starters. But, in contrast to the previous work and our hypothesis, the current starters may have improved performance following the competitive season. Specifically, starters increased CMJ peak force production 14% at post-season compared to pre-training and pre-season times points (2.41 BW vs. both 2.11 BW); whereas, the non-starters exhibited an insignificant 5% and 4% increases in peak force at the post-season time point. Again, methodological differences with McLean et al and Kramer et al may contribute to the current discrepancy. Although McLean et al. did not include specific training methodology for their participants[33], Kraemer et al. reported no training differences between starters and non-starters[57]. The current starters, however, performed a different training regimen, designed to manage their workload and limit the accumulation of fatigue during the competitive season, compared to non-starters (Appendix B).

Despite not observing significant group differences in isokinetic strength and power and individual CMJ measures, performance of the CMJ task accurately predicted 95.5% (8 out of 9) of the tested athletes defined as a starter. The high accuracy of CMJ performance to predict a starter may be a reliable method for sports performance coaches and athletic trainers to monitor athlete performance, and further work is needed to determine the specific CMJ variables important to monitor. Additionally, these results highlight the ability of the CMJ task to differentiate between groups, and the ability of the CMJ task to differentiate between other groups (such as those at risk for injury) warrants further study.

<u>Freshman vs. Non-Freshman</u>

First-year collegiate athletes demonstrate greater rates of injury than non-first-year athletes[31,32], possibly indicative of altered responses to training loads in these athletes. For example, Wolf et al. reported freshman (i.e. first-year) female collegiate swimmers averaged nearly twice the number of injuries compared to non-first-year athletes, with the number of injuries trending downward with each increase in year of eligibility[31]. Contrary to our hypothesis, there were no significant differences in isokinetic strength or power for first-year athletes compared to non-first-year athletes. But, the first-year athletes exhibited significantly greater CMJ height (18%) following the competitive season. While first-year athletes jumped higher at the post-season mark, the reason behind this increase is unclear, as significant differences in other measured CMJ variables, which may be more sensitive to muscular fatigue[27], were not exhibited between first- and non- first year athletes at the post-training time point. However, the results do coincide with previous research from Hunter et al., which identified significant increases in jump height in college basketball from freshman to sophomore years[61].

Although first-year and non-first-year athletes demonstrated similar changes in CMJ performance, analysis of the CMJ variables was able to predict group membership with approximately 86% accuracy. Specifically, analysis of CMJ measures predicted of 5 of 7 first-year and 14 of 15 non-first-year athletes, but the CMJ performance in general and explicit CMJ measures specifically were not statistically significant (i.e., Wilks Lambda greater than 0.05) between groups. Although CMJ measures discriminated 86% of first-year athletes, further study is warranted to determine the specific CMJ measures for coaches and trainers to monitor to quickly and reliability identify performance for all collegiate soccer athletes in general and athletes are high risk of injury specifically.

Limitations

This study was limited by participant availability. All participants were members of a collegiate soccer team, and because of their busy schedules were unable to complete testing on a single day. Thus, testing often occurred over two or three days, giving some participants an extra 24 to 48 hours of recovery following either off-season training or the competitive season. While this may have had some influence on isokinetic data, the specific CMJ jump variables for this study were selected due to lasting decrements which last up to 72 hours post-fatigue[27]. Moreover, the participant time constraints limited the number of testing sessions each could perform. Collecting strength and performance data more periodically throughout training and the competitive season may have provided a broader view of changes experienced over the course of the competitive season and off-season training. Although, the three chosen time points suffice in giving overall and group changes due to training loads over off-season training and the competitive season. Lastly, due to circumstances common to collegiate athletes, such as injury or leaving the program, only twenty-two athletes performed all three testing sessions. Although this sample is sufficient to test our Aims, a larger data set may have led to increased statistical significance between groups, while also possible providing enough data to establish CMJ variables which can be used to quickly and reliably monitor training loads.

Conclusion

In conclusion, a simple CMJ task shows promise as a tool for athletic trainers and sports performance coaches to reliably monitor female soccer performance in general and training loads specifically. Immediately following the competitive season, the current athletes increased isokinetic strength and power as well as CMJ performance, with changes in CMJ peak power, LPF, and JH exhibiting a moderate to strong relation with changes in quadricep and hamstring isokinetic strength and power. Yet, following off-season training, a similar relation between changes in CMJ performance and isokinetic strength and power was not observed. These same CMJ measures accurately identified 96% of the athletes defined as either a starter or non-starter, and 86% of first-year athletes and as such, may serve as an effective tool for identifying improved strength and power, and performance differences for members of a collegiate soccer team.

CHAPTER FOUR: CONCLUSION

Introduction

The purpose of this study was to: (1) determine the feasibility of the CMJ task to quickly and reliably monitor decrements in force or power following offseason training and the competitive season and, 2) determine whether specific CMJ measures could successfully identify starters and/or first-year athletes. Key findings partially support both hypotheses, as CMJ performance measures exhibited moderate to strong relations to isokinetic strength and power changes exhibited immediately following off-season training and competitive season. Yet only starters, and not first-year athletes, could be accurately predicted from CMJ performance.

Key Findings

Contrary to our hypothesis and existing literature, the tested athletes increased hamstrings and quadriceps strength and power following the competitive soccer season. Specifically, following the competitive season, athletes exhibited significant increases in isokinetic power and strength of the quadriceps and hamstrings muscles for both the dominant and non-dominant limb and jump height, peak force and power, and the maximum rate of force and power production measured during the CMJ. Considering the increase in CMJ, performance exhibited a moderate to strong relation to the increases isokinetic strength and power exhibited by the athletes following the competitive season, quantifying CMJ performance shows promise as an efficient, reliable tool for monitoring athlete increases muscular strength and power. CMJ performance, however, did not exhibit similar relation to decreases in isokinetic strength and power observed following off-season training. The CMJ task may be better suited to monitor increases, rather than decreases in athlete performance. But, this warrants further study, as the current athletes exhibited, albeit mostly insignificant, reductions in strength and power following training.

CMJ measures were able to accurately identify 96% of starters and 86% of first-year athletes, although first-year athletes did not differ in CMJ performance from non-first-year athletes. Quantifying CMJ performance may detect underlying differences in performance not captured by CMJ or isokinetic strength and power variables separately. Future research should look to determine the explicit CMJ measures that identify these group differences.

Significance

High rates of injury in collegiate female soccer athletes highlight a need for an affordable, efficient, and accurate method for athletic trainers and sports performance coaches to monitor training loads during training and the competitive season. The current experimental outcomes contradict the recent findings of McLean et al. that starters on a female soccer team exhibit decrements in muscular power following the competitive season[33]. Specifically, the female soccer athletes currently tested exhibited increases in muscular strength and power measured with both the isokinetic dynamometer and force plate during a countermovement jump following the competitive season. Changes in these CMJ measures exhibited moderate to strong relations to changes in isokinetic strength and power, demonstrating promise in the ability of the CMJ task to reliably measure changes in athlete strength and power. But, the same CMJ measures exhibited limited relation to decrements in isokinetic strength and power exhibited following off-season training. These experimental results may indicate that the CMJ task is better suited for measuring increases in strength and power rather than decrements.

Discriminant analysis on CMJ performance variables was able to accurately classify 96% of starters and 86% of first-year athletes. The CMJ measures, however, only exhibited a significant difference between starters and non-starters. Although CMJ variables classified nearly all first-year athletes their CMJ performance was not statistically different from non-first year athletes. This new finding, paired with significant correlations between CMJ performance and isokinetic strength and power, help to further establish the CMJ task as a prime candidate as a primary tool for monitoring athlete training loads in collegiate female soccer settings.

Limitations

This study was limited by participant availability. All participants were members of a collegiate soccer team, and because of their busy schedules were unable to complete testing on a single day. Thus, testing often occurred over two or three days, giving some participants an extra 24 to 48 hours of recovery following either off-season training or the competitive season. While this may have had some influence on isokinetic data, possibly allowing time for strength and power to recover, the specific CMJ jump variables for this study were selected due to lasting decrements which last up to 72 hours post-fatigue[27]. Moreover, the participant time constraints limited the number of testing sessions each could perform. Collecting strength and performance data more periodically throughout training and the competitive season may have provided a more specific view of where athletes begin to see decrements (or increases) in measured variables while also allowing for a larger number of comparisons for discriminant and regression analyses. Although, the three chosen time points suffice in giving overall and group changes due to training loads over off-season training and the competitive season. Lastly, due to circumstances common to collegiate athletes, such as injury or leaving the program, only twenty-two athletes performed all three testing sessions. Although this sample is sufficient to test our Aims, it may have reduced statistical power, and a larger data set may have led to increased statistical significance between groups, while also possible providing enough data to establish CMJ variables which can be used to quickly and reliably monitor training loads.

Future Work

The current athletes demonstrated increased strength, power, and CMJ performance following the competitive season. These outcomes are in contradiction to previous research in which soccer athletes demonstrated reduced strength and power upon completion of the season. As these decrements are reportedly associated with increased injury risk and reduced performance, it is imperative for researchers to further investigate muscular changes of soccer athletes throughout the season. Continued research regarding methods of training, and differences in response to training for starters and non-starters may possibly provide coaches with the knowledge to maintain performance and reduce injury risk throughout the season.

These current experimental outcomes demonstrate the CMJ may be a promising tool to monitor athlete performance (i.e., strength and power) improvements following periods of training and/or competition. Yet, the specific CMJ performance measures that are both valid and reliable for monitoring performance changes is currently unknown and warrants future study. Additionally, it is unclear if specific CMJ measures can accurately monitor decrements in athlete muscular strength and power. Further research is warranted to determine if explicit CMJ measures can effectively quantify decrements in performance and subsequent increases in injury risk.

The current discriminant analysis demonstrated CMJ task can accurately identify starters and first-year athletes on a collegiate soccer team based on variations in CMJ performance measures. Future research should expand the current work beyond female soccer as monitoring performance of other sexes and sports is warranted. Finally, expanding the work beyond the chosen groups is also necessary, as identifying athletes that are at risk for future injury or determining whether an athlete is ready to return form injury would be useful for athletic trainers and sports performance coaches.

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APPENDIX A

Additional Tables

Table A. 1 CMJ performance measures of first-year (Freshman) and non-first-year (Non-Freshman) athletes by time point

	Pre-Training		Pre-Season		Post-Season	
	Freshman	**Non-Freshman**	**Freshman**	**Non-Freshman**	**Freshman**	**Non-Freshman**
Peak Power	$4.43 \pm 0.58^{\#}$	$4.56 \pm 0.71^{\#}$	4.59 ± 0.66	4.57 ± 0.54	5.11 ± 0.72	4.64 ± 0.49
MRPD	$32.13 \pm 7.35^{\#}$	$31.59 \pm 7.99^{\#}$	$32.76 \pm 6.60^{\#}$	$31.02 \pm 6.59^{\#}$	37.89 ± 7.95	36.24 ± 7.59
Peak Force	$2.11 \pm 0.17^{\#}$	$2.20 \pm 0.21^{\#}$	$2.23 \pm 0.17^{\#}$	$2.17 \pm 0.17^{\#}$	2.33 ± 0.21	2.35 ± 0.21
MRFD	9.75 ± 2.17	10.48 ± 2.90	9.56 ± 3.32	9.85 ± 2.54	10.93 ± 2.88	12.34 ± 4.34
RSI	0.56 ± 0.26	0.57 ± 0.17	0.46 ± 0.10	0.49 ± 0.05	0.60 ± 0.32	0.63 ± 0.37
JH$^{\%}$	$0.27 \pm 0.04^{\#}$	0.29 ± 0.06	$0.27 \pm 0.05^{\#}$	0.28 ± 0.04	$0.32 \pm 0.06^{*}$	0.27 ± 0.04
LPF	3.57 ± 0.79	3.38 ± 0.60	3.62 ± 0.74	3.35 ± 0.44	3.62 ± 0.67	3.31 ± 0.41
RNI	0.26 ± 0.04	0.24 ± 0.04	0.27 ± 0.04	0.25 ± 0.03	0.26 ± 0.02	0.24 ± 0.02
Asymmetry	-0.26 ± 2.14	-0.64 ± 2.52	-0.04 ± 3.88	0.26 ± 2.86	1.05 ± 5.74	-0.31 ± 4.07

***Denotes significant difference from non-freshman ($p<0.05$)**

$^{\#}$Denotes significant difference from post-season

$^{\%}$Denotes significant time by group interaction

Table A. 2 CMJ performance measures of starters and non-starters by time point

	Pre-Training		Pre-Season		Post-Season	
	Starter	Non-Starter	Starter	Non-Starter	Starter	Non-Starter
Peak Power	$4.44 \pm 0.74^{\#}$	$4.57 \pm 0.63^{\#}$	4.45 ± 0.59	4.66 ± 0.55	4.74 ± 0.52	4.84 ± 0.67
MRPD	$29.28 \pm 7.40^{\#}$	$33.48 \pm 7.57^{\#}$	$29.12 \pm 6.92^{\#}$	$33.27 \pm 5.84^{\#}$	37.67 ± 6.94	36.25 ± 8.14
Peak Force$^{\%}$	$2.13 \pm 0.19^{\#}$	2.20 ± 0.21	$2.14 \pm 0.18^{\#}$	2.23 ± 0.15	2.40 ± 0.19	2.31 ± 0.20
MRFD	9.75 ± 3.14	10.59 ± 2.34	9.69 ± 2.94	9.80 ± 2.71	12.57 ± 4.66	11.44 ± 3.49
RSI	0.53 ± 0.15	0.59 ± 0.22	0.49 ± 0.05	0.48 ± 0.08	0.86 ± 0.49	0.48 ± 0.07
JH	0.28 ± 0.06	0.28 ± 0.05	0.28 ± 0.05	0.28 ± 0.05	0.28 ± 0.04	0.29 ± 0.05
LPF	3.33 ± 0.53	3.52 ± 0.74	3.20 ± 0.40	3.59 ± 0.60	3.31 ± 0.43	3.48 ± 0.57
RNI	0.25 ± 0.03	0.25 ± 0.04	0.25 ± 0.03	0.26 ± 0.03	0.24 ± 0.03	0.25 ± 0.02
Asymmetry	-0.39 ± 2.71	-0.61 ± 2.20	0.11 ± 2.88	0.20 ± 3.40	1.66 ± 2.74	-0.80 ± 5.32

$^{\#}$Denotes significant difference from post-season

$^{\%}$Denotes significant time by group interaction

APPENDIX B

Athlete Training information

All athlete training and conditioning was provided, and supervised by, team athletic coaches and sports performance trainers. All participated in a 6-week offseason training program designed to increase strength and power. During the season, starting and non-starting athletes differed in training as shown below (**Table B.1**). Full workouts consisted of strength and power training lasting approximately 40 minutes, while a light training day consisted of mobility work and active recovery lasting approximately 30 minutes. Tuesday and Wednesday workouts were accompanied by full practices lasting approximately 2 hours, while Thursday and Saturday practices included game preparation and lasted approximately 1.5 hours.

Table B. 1 Training Schedules for Starters and Non-Starters

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Starter	Rest	Light Training	Full Workout	Light Training	Game	Light Training	Game
Non-Starter	Rest	Full Workout	Full Workout	Light Training	Rest	Light Training	Rest

APPENDIX C

Alternative Regression Analysis

The absolute change for both CMJ and isokinetic measures for both limbs (dominant and non-dominant) following both training and competitive season were submitted to a stepwise linear regression to determine if CMJ performance measures predicted changes in isokinetic muscular strength and/or power. For each step, independent variables were retained in the final equation if $p < 0.05$, while a significance of $p > 0.10$ was used to exclude variables from each stepwise model.

Results

Changes in RNI and peak force were found to have a significant, moderate relation with changes in muscular strength and power. Specifically, RNI was a significant predictor of hamstrings torque ($r = 0.321$, $b = -2.256$ and $p = 0.044$), and a 10% increase in RNI predicted a 0.23 Nm/kg decrease in peak hamstrings torque (**Fig C.1**). Peak force as a predictor of quadriceps torque ($r = 0.321$, $b = 0.708$ and $p = 0.044$) and quadriceps power ($r = 0.362$, $b = 0.727$ and $p = 0.022$). A 10% increase peak force predicted a 0.071 Nm/kg and 0.073 W/kg increase in peak quadriceps torque and average power respectively (**Fig C.2 and C.3**).

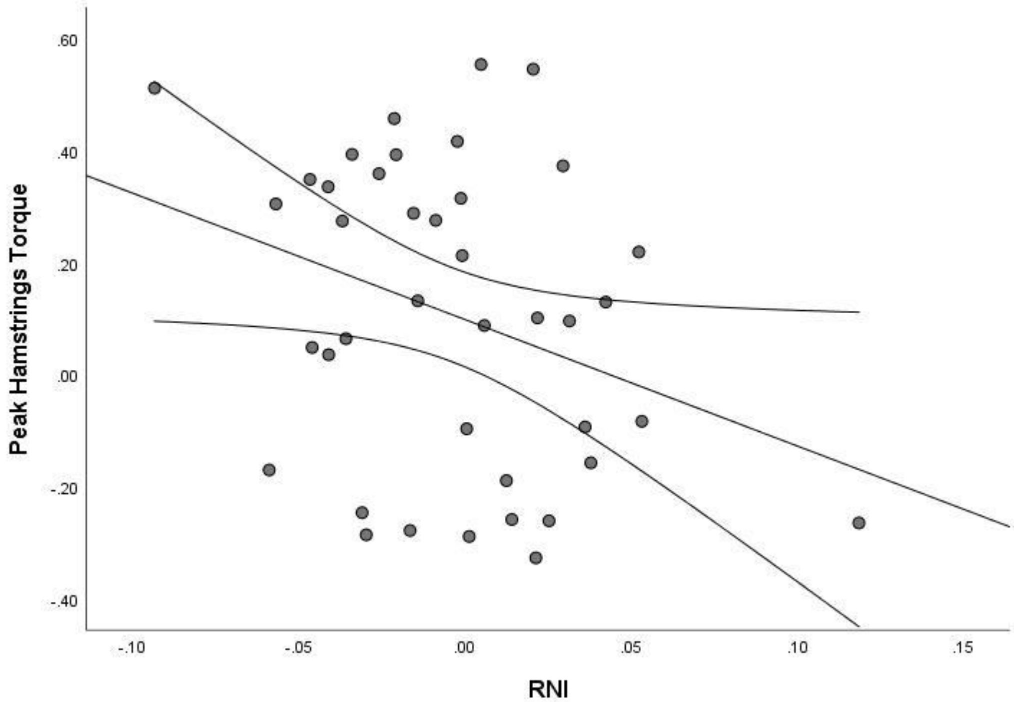

Figure C. 1 Change in peak hamstrings torque by RNI

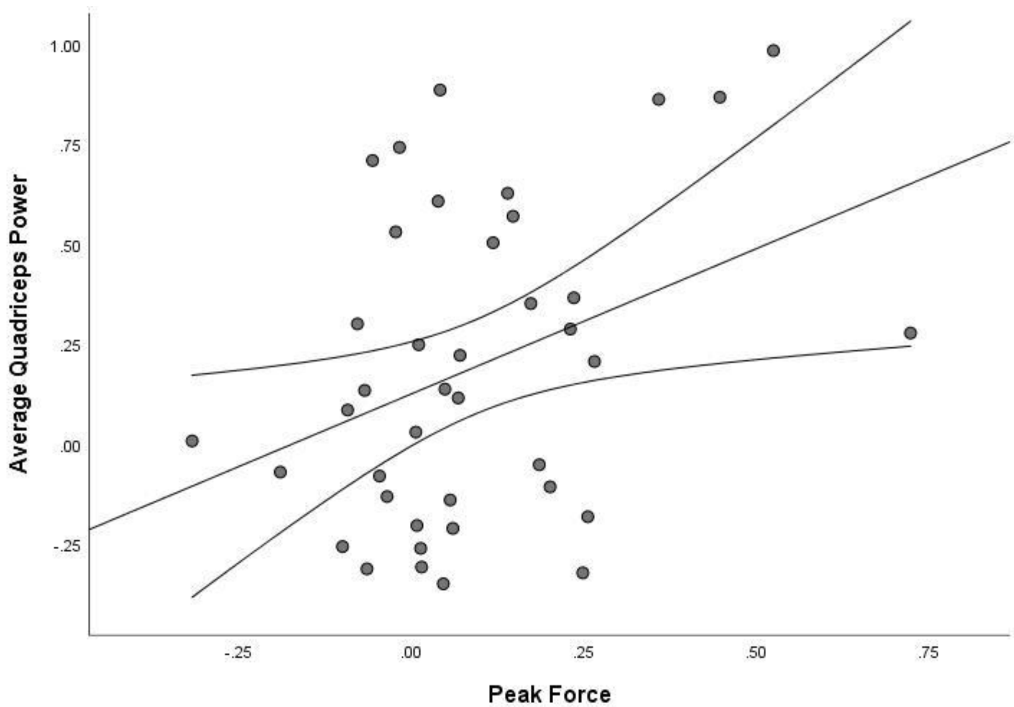

Figure C. 2 Change in peak quadriceps torque by peak force

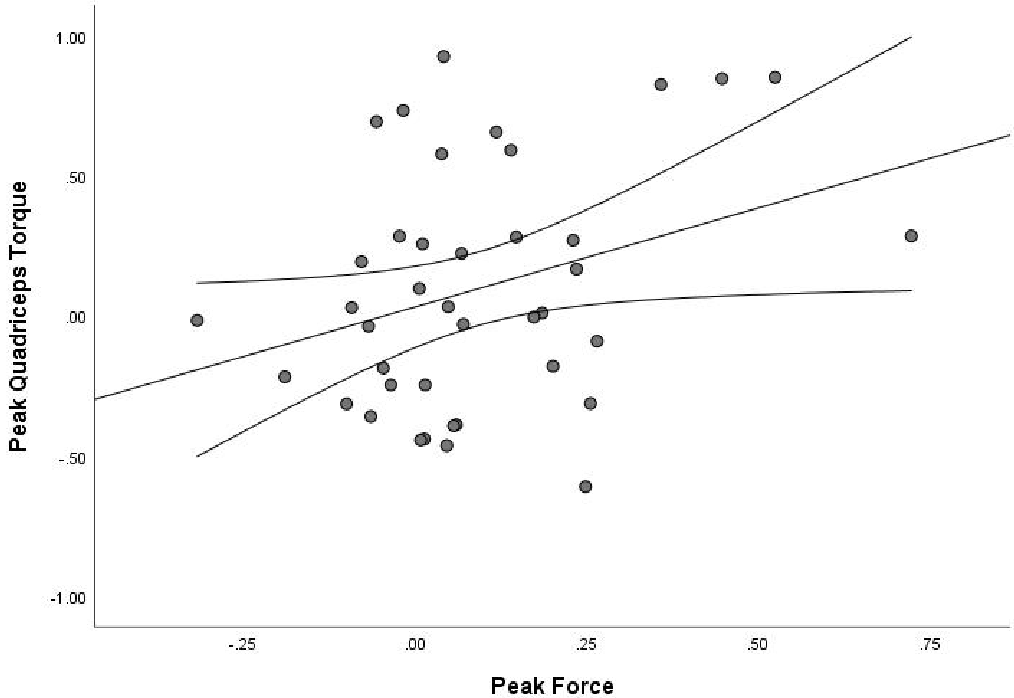

Figure C. 3 Change in average quadriceps power by peak force