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An Examination of Inter-Limb Functional Asymmetry After a Fatiguing Bout of Exercise in High Level Soccer Players

by

Nestor Urrea

Bachelor of Science
University of South Florida, 2021

Submitted in Partial Fulfillment of the Requirements

For the Degree of Master of Science in

Exercise Science

Arnold School of Public Health

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Accepted by:

Shawn M. Arent, Director of Thesis

Bridget McFadden, Reader

Jay Patel, Reader

Ann Vail, Dean of the Graduate School

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DEDICATION

This thesis is dedicated to my parents, Fernando and Claudia, and to my sister, Clara. Thanks for the endless love, support, and encouragement. I will always be grateful to you because thanks to your sacrifices, I have been able to chase my dreams. You are my motivation to be the best in what I do. Love you all!

ACKNOWLEDGEMENTS

I would like to thank my advisor and mentor, Dr. Shawn Arent for the guidance in the last two years and for being an inspiration for my academic and professional career. In addition, I would like to thank Dr. Bridget McFadden for all the support through this process and for the confidence that she gave me to conduct and complete this study. I would also like to thank Dr. Jay Patel for always being open to share his knowledge and expertise.

I would like to give a huge recognition to the PhD students, Gianna, Blaine and Alexa, to Nate, who shared this experience with me since day one, and to the rest of the USC Sport Science Lab research staff. This research would have not been completed without your help. I will always be grateful for that.

Lastly, I want to acknowledge the USC women's soccer team. To all coaching staff and players, thank you for making my graduate experience an incredible and unforgettable one.

ABSTRACT

INTRODUCTION: Inter-limb functional asymmetries greater than 15% have been linked to a greater incidence of injury. Moreover, asymmetries greater than 10% have shown greater risk of injury and worsened sport performance, especially for strength and power capabilities, in athletes of multiple sports. Fatigue and sex are factors that seem to influence injury rates as well as greater asymmetries between limbs. This research project aims to investigate the effects of a fatiguing bout of exercise in strength and power inter-limb functional asymmetries in male and female soccer players. It was hypothesized that strength and power asymmetries are negatively affected after a treadmill-based simulated match protocol in male and female soccer players. It was also hypothesized that females will show more exacerbation of strength and power asymmetries compared to males.

METHODS: 38 high level soccer players (Males n =18; Females n =20) participated in an experimental study that consisted of two lab visits in a span of one week. Each participant executed strength and power performance tests pre and post a 90-minute simulated game treadmill protocol. Performance tests included a single-leg press, bilateral countermovement jump (CMJ), unilateral countermovement jump (SLCMJ), bilateral drop jump (DJ) and unilateral drop ump (SLDJ). All performance metrics were analyzed using a paired t-test pre vs post as well as for sex comparison analysis. Statistical significance was set at α=0.05.

RESULTS: Significant decreases in jump height were observed in CMJ, DJ, SLCMJ and SLDJ ($P<0.05$) as well as reduction in number of repetitions on the single-leg press ($P<0.05$). Male athletes showed greater significant decreases in performance in comparison to female athletes. In addition, significantly higher internal load was seen in males during the fatiguing protocol.

DISCUSSION: Fatigue negatively affected inter-limb functional asymmetries in high level soccer players, especially in male athletes. Sex differences in performance post intervention seem to be due the higher workload during treadmill protocol. More research is still needed to develop a standardized method to measure inter-limb asymmetries and its influence in sport performance and return to play protocols.

CONCLUSION: A 90-minute exercised-induced fatigue protocol that simulated soccer physical demands did negatively affect power and strength asymmetries in the lower limbs in high level soccer players. In terms of sex differences, men presented higher fatigue index which led to greater changes in inter-limb asymmetries for strength and power compared to women.

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LIST OF ABBREVIATIONS

Avg........Average

BF........Body Fat

CM........Centimeter

CMJ........Countermovement Jump

DJ........Drop Jump

FP........Force Plates

HR........Heart Rate

JH........Jump Height

JM........Jump Mat

KG........Kilograms

L........Left

mRSI........Modified Reactive Strength Index

R........Right

RPE........Rating of Perceived Exertion

RSI........Reactive Strength Index

SD........Standard Deviation

SL........Single Leg

SLCMJ........Single-Leg Countermovement Jump

SLDJ........Single-Leg Drop Jump

YRS........Years

5RM........Five-Repetition Maximum

CHAPTER 1

INTRODUCTION

Symmetry is defined as the similarity or exact correspondence of parts facing each other when split along a given axis. This correspondence could refer to similarities in form, size, shape, or another set of characteristics. In terms of sport performance, asymmetry refers to inter-limb differences which can be assessed via body composition, strength, and/or power, all of which may play a crucial role in a given sporting event. Most team sport athletes are required to perform unilateral and bilateral movements which make inter-limb differences a key factor that may affect sport performance. There are various ways to characterize inter-limb differences. For example, comparisons can be made between dominant and non-dominant or stronger and weaker limbs, with asymmetry represented by percent differences from one limb to the other (Bishop et al., 2018). Prior work by Grindem et al. (2011) and Impellizzeri et al. (2007) has shown that inter-limb asymmetries greater than 15% are associated with a greater incidence of injury. Furthermore, inter-limb asymmetries can also influence return to play protocols and injury risk. The currently proposed benchmark for safe return to sport and a feasible marker of successful rehabilitation is an asymmetry between limbs less than 10%. Additionally, some studies have linked asymmetries of 10% or more to an increased risk of injury and worsened performance, such as lower jump heights in a bilateral countermovement jump (Bell et al., 2014), impaired change of direction capabilities, and reduced sprint speeds; however, these findings have not been consistent throughout the literature (Lockie et al., 2014).

Previous research has implemented a variety of methods to evaluate asymmetries in athletes. Methods such as the isometric mid-thigh pull (Bailey et al., 2013), isometric unilateral and bilateral squat (Hart et al., 2014), and isokinetic peak torque have been used to assess sub-maximal and maximal strength asymmetries. Power differences have been measured using jump variations, including single-leg countermovement, broad, vertical, and lateral jumps (Harry et al., 2021; Hoffman et al., 2007; Lockie et al., 2014). Additionally, other performance traits have been assessed across studies including change of direction, speed or agility (Hoffman et al., 2007; Lockie et al., 2014) as well as jump height and measures of power output (Bailey et al., 2013). Despite the assessment of various aspects of athletic performance through a wide range of techniques, additional research is still needed to determine accurate and reliable methods to assess inter-limb asymmetries that can be applied to high-level athletes in diverse training settings.

In team sports, a greater incidence of injury has been observed when athletes experience increased fatigue, a phenomenon which compounds during later stages of competition (Ekstrand et al., 2011; Hawkins & Fuller, 1999; Pinto et al., 1999). Soccer, basketball, and lacrosse are examples of sports that may display this increased incidence of injury due to the intensity, duration, and unpredictability of competition. Recent work by Bromley et al. (2021) has observed that inter-limb asymmetries are sensitive to fatigue, with the largest increases found post-soccer match (Bromley et al., 2021). Additionally, some have suggested that inter-limb asymmetries in conjunction with exercise-induced fatigue are risk factors for non-contact related injuries (Heil et al., 2020). Due to the concerns related to injury rates and reductions in performance, further research is warranted to examine asymmetries in measures of both strength and power after a fatiguing bout of exercise. This information could bolster the scientific community's understanding as to the degree to which asymmetries become exacerbated under fatigue, and how they may relate to performance outcomes.

A few studies have suggested that differences in lower-limb injury rates exist among men and women. For example, greater rates of anterior cruciate ligament (ACL) injuries among women when compared to male athletes in similar sporting events have been reported (Arendt & Dick, 1995). Despite previous research demonstrating that the physical demands of a soccer match are similar between males and females (McFadden et al., 2020), sex differences in asymmetries, as well as an understanding of how inter-limb asymmetries are influenced under conditions of fatigue, may provide insight into some of the underlying mechanisms for increased injury rates over the course of a soccer game. Both consistency and experimental control are necessitated to assess the effect of exercise-induced fatigue on inter-limb asymmetries (Heil et al., 2020), particularly between men and women.

In a study conducted by Bishop et al. 2019, authors evaluated the relationship between inter-limb asymmetries and performance outcomes such as speed and change of direction capabilities in female soccer players. Unilateral countermovement jump and unilateral drop jump were performed and compared to the result in the 10 m and 30 m speed tests and change of direction speed test. Results showed that unilateral drop jump was correlated with slower times in all the performance tests. Researchers concluded that the DJ is a useful assessment to detect inter-limb asymmetries that could potentially produce adverse effects in speed and change of direction abilities which are an essential part of soccer. Another study conducted by the same research team recently examined the seasonal variation of asymmetries between lower limbs in academy soccer players. CMJ and SL CMJ, linear speed and change of direction tests were conducted at the pre, mid, and end of the season. Metrics taken into account included jump height, mRSI and time to takeoff and inter-limbs asymmetries were calculated for each variable using force platforms. Results showed that the SL CMJ was one of the tests that was more sensitive to changes in performance, especially for jump height, and changes in inter-limb asymmetries were able to be detected throughout the season (Bishop et al., 2023).

In previous work from Heil et al. in 2020, authors analyzed the influence of exercise-induced fatigue on inter-limb functional asymmetries. In this systematic review, studies that included fatiguing protocols using a variety of modalities such as running, jumping (e.g., CMJ), rowing, squatting, soccer, combination of different exercises, between others. All articles that were included in the review used physical active and athletic population from different modalities and sports as participants. Also, there were more males than females examined across the articles utilized for this review. Researchers concluded that future research that aims to analyze the effects of exercise-induces fatigue on inter-limb asymmetries need more standardization and consistency. Furthermore, it is crucial to measure pre and post fatiguing protocol using sport-specific movements or tasks to truly identify the possible risk of injury, especially for non-contact injuries, due to inter-limb asymmetries under the influence of fatigue (Heil et al., 2020).

Bishop et al. reviewed the various methods in which researchers and coaches are measuring inter-limb asymmetries for strength and power and which training interventions have been used to improve these asymmetries. The authors concluded that the current asymmetry literature is too limited to draw conclusions on best practices to assess and intervene inter-limb functional asymmetries. Methodology used in the current literature is very variable, which makes it very difficult to compare results with other studies. For this study, we chose to use the force plates (*Hawkin Dynamics Inc., Westbrook, ME*) and the jump mat (*Just Jump, Probotics Inc., Hunstville, AL)* for our jump testing protocol. Both pieces of equipment were chosen because of their feasibility and portability, and they are two of the most used types of equipment in the inter-limb asymmetry literature, laboratory settings and collegiate teams. It is necessary to create a standardized methodology for the implementation of these assessments to optimize the analysis and interpretation of the results. For that reason, future research is needed to develop enhanced methodologies to examine and address inter-limb functional asymmetries within the sport (Bishop et al., 2022).

This research project aims to provide a targeted approach to better understand athlete readiness and performance optimization by developing assessments of injury risk as well as strength and power imbalances and may provide the foundation for generating novel methods to evaluate player readiness and return to play criteria. If sex differences in asymmetry rates are found to occur after a fatiguing bout of exercise, this may provide further insight into mechanisms behind differences in injury rates, which may have important implications for strength training and treatment interventions.

CHAPTER 2

METHODS

2.1 PARTICIPANTS

Forty high level soccer players, consisting of 20 males and 20 females were recruited for this experimental study. The recruitment process primarily targeted athletes from the University of South Carolina men's and women's soccer teams. Additional participants were recruited from other college programs and semi-professional soccer teams. To be eligible to participate, individuals must have met the following inclusion criteria:

- High level soccer player between the ages of 18 and 35 (inclusive).
- In good health as determined by medical history and cleared to participate in physical activity by a medical professional.
- Currently playing at a high-level setting (e.g., college soccer team and semi-professional or professional team).

Participants were excluded if they had any current or have had any musculoskeletal injury in the past six months that prevent them from completing the exercise protocol. Prior testing, all participants were screened by filling a medical, training and injury history questionaries, and signed their written and dated informed consent to participate that was approved by the University of South Carolina Institutional Review Board.

2.2 STUDY DESIGN

The study consisted of two visits, screening and familiarization (Visit 1) and experimental visit (Visit 2). During visit 1, participants completed paperwork that included an informed consent, health and training & injury questionnaires, and a 24-hour dietary intake. In addition, body composition assessments, familiarization with warm-up and performance tests, and a 5RM single leg press were also performed during this visit. Visit 2 consisted of completion of a 24-hour diet recall, warm-up, pre-jump and strength tests, fatiguing protocol on treadmill and the post- jump and strength testing. Both visits were scheduled in a period of 7 days, where the visit 2 took place at least 48 hours after the first visit for each participant. Furthermore, the two sessions took place at the same time of day or 1-2 hours apart compared to the time of the first session. Participants attended both visits at the Sport Science Lab at the University of South Carolina (Columbia, SC) over the course of the study.

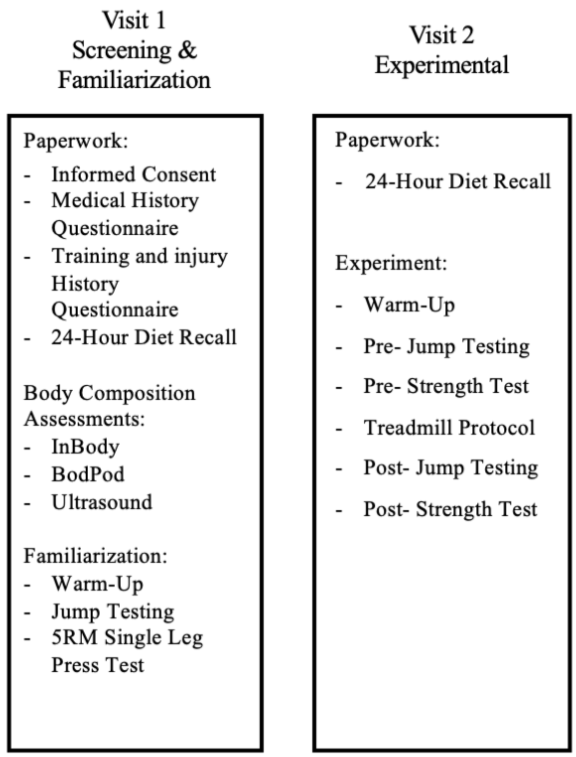

Figure 2.1 *Study Design: Visits*

2.3 BODY COMPOSITION

Height was measured using a stadiometer. Body composition was assessed via air-displacement plethysmography (*Bod Pod, COSMED, Concord, CA*). A prediction equation was used to determine thoracis gas volume (McCrory et al. 1998), and the Brozek density model was used to determine body fat percentage (Brozek, 1956). Bio-electrical Impedance Analysis (BIA) was performed to measure weight and segmental lean body mass differences between lower extremities (*InBody 270, Biospace, California, USA*). Participants wore compression shorts and sports bras (for females), and they were asked to refrain from food and physical activity or exercise for ≥ 2 hours. All calibrations and tests were conducted according to the manufacturer's guidelines.

Quadriceps muscle thickness was measured with a 10 MHz ultrasound transducer (*iQ, Butterfly Network Inc. Guilford, CT, USA*). Participants laid supine on a table and a foam roll was placed under the knee to accomplish a passive flexion and ensure relaxation of the quadriceps. A researcher took two images at each leg with the probe perpendicular to the femur at 50% distance from the greater trochanter of the femur to the lateral epicondyle of the femur to measure quadriceps thickness (Loenneke et al., 2017; Matta et al., 2017).

2.3 PERFORMANCE TESTING

Warm-Up

Subjects completed a standardized dynamic warm-up. Warm-up consisted of a five-minute self-pace activation on a treadmill followed by a dynamic warm-up. A researcher instructed participants to perform a series of exercises going down and back on a turf area approximately 15 yards long. The exercises that were used included high kick, walking scoops, knee hugs, quad stretches, lunges, figure 4s, side lunges, side lunges, hip flexor stretches stretches, high knees, butt kicks, side shuffles and carioca. Participants were familiarized with these movements since these are commonly implemented by strength and soccer coaches in typical warm-up protocols.

Jump Testing

Inter-limb asymmetries for power were assessed utilizing two maximal bilateral countermovement vertical jumps (CMJ) followed by two maximal single-leg countermovement jumps (SL CMJ) as well as two maximal drop jumps (DJ) and single-leg drop jumps (SL DJ) using force plates (FP) (*Hawkin Dynamics Inc., Westbrook, ME*) to assess bilateral and unilateral jump height, reactive strength index (RSI), modified reactive strength index (mRSI), and percentage of asymmetry on average rate of force production. RSI and mRSI are measures that represent an athlete's strength capabilities. The difference between these two variables is that RSI is the ratio between flight time by ground contact time whereas mRSI is the ratio between jump height and ground contact time. Just jump mat (JM) was also used to measure jump height (*Just Jump, Probotics Inc., Hunstville, AL*). A 15.24 cm (6 in) step box was utilized for the bilateral and single leg drop jumps (Maloney et al., 2017). The step box was adjusted when performing drop jumps on JM to account for height difference between force plates and mat. Each participant executed two attempts (or three attempts if the jump heights of first two attempts had a ≥ 10% difference) per each type of jump with thirty seconds of rest between attempts. All jumps were performed ensuring that participants placed their hands on each side of their hips and that they remained in that position throughout the jump. Jumping with hands on the hips minimizes the assistance from arm swing momentum during the movement and the jump is being produced mostly by muscles groups of the lower body. In addition, full extension of the knees was encouraged during the flight time of all jumps to control for possible incorrect flight time measurements. Jump attempts were repeated if participants did not keep their hands on their hips or if they flexed their knees during the flight time of any jump. The average of the two highest jump heights were used in our analysis. The depths of the eccentric phase of the jumps were self-selected by the participants. A researcher instructed participants to perform the jumps while other researcher(s) recorded the jump heights. Other variables were automatically recorded and saved by the Hawkin Dynamics Software. Jump testing was implemented in the following order: CMJ-FP → CMJ-JM → DJ-FP → DJ-JM → SL CMJ-FP → SL CMJ-JM → SL DP-FP → SL DJ-JM. Single leg jumps were performed with alternating legs and randomized to start with the dominant leg first. This jump testing protocol was implemented before and after the fatiguing bout of exercise on the treadmill.

Strength Testing

During visit 1, a 5-repetition maximal (5RM) single-leg press was conducted using NSCA guidelines (*Haff G and Triplett NT. Essentials of Strength Training and Conditioning 4th Edition. Champaign, IL: Human Kinetics, 2016, Pp 452-454*). The leg press machine used on this test was the Sorinex leg press machine (Model#P00024) (*SORINEX Exercise Equipment, Lexington, SC*). Before starting the test, researchers requested each participant to sit on the machine and picked their preferable pad and sled height on the machine. Pad and sled heights were noted to use on their second visit. In addition, measurements of foot placement on the sled were taken in order to maintain consistency between visits. Marks were made at the top, bottom, internal and external borders of each foot and measurements from those marks to the top, bottom and each lateral border of the sled were noted. Participants performed two warm-up sets and then performed up to six attempts to achieve their 5RM for each leg. For all attempts, each subject was asked to perform five repetitions with the adjusted weight. Individuals had 2 minutes of rest in between the warm-up sets and 3 minutes of recovery between attempts, and the adjustments of weight for each set were based on the participant's feedback on how hard and/or how close the set was compared to their 5RM and the judgment of the researchers witnessing the test. Subjects always started each set with their dominant leg. The lowest depth of the eccentric portion of the movement was determined to be at 90 ° angle of the knee joint. A safety pin was placed on the leg press machine to ensure that the sled touched the safety pin when the knee joint was at the requested depth. Lastly, subjects were encouraged to use the same pair of shoes for strength tests on both visits.

The strength test used during visit 2 was a single set to failure, with resistance set at 90% of the participant's 5RM for each leg. Subjects performed two warm-up sets with two minutes of rest in between followed by the set to failure with the calculated resistance. Researchers ensured that the jump and sled heights, foot placements measurements and safety pin location were the same as their first visit. The strength test was conducted before and after the fatiguing protocol on the treadmill.

Fatiguing Bout of Exercise

Participants performed a 90-min simulated match protocol on a high-speed treadmill (*HPCosmos T170, COSMED, Concord, CA, USA*) after initial inter-limb testing which was designed to mimic the demands of a soccer match in a laboratory setting to control for extraneous variables such as the environment, opponents, travel, or player positions. The simulated match protocol included two 45-min halves separated by a 15-min half-time recovery period with varying speeds and intensities (e.g., standing, walking, jogging, running, and sprinting) over the two halves to reproduce in-game sprints and changes in speed at a constant 2% grade. Subjects wore a chest-strap heart rate sensor (*Polar Team Pro, Polar, Lake Success, NY, USA*) to monitor heart rate throughout the whole session. Rating of perceived exertion (RPE) was assessed at the end of each half using the Borg's 6 to 20 scale (*Borg, 1998*). Changes in speed were automatically applied by the treadmill's software and a researcher gave a notice to participants before each change of intensity. Subjects were only allowed to consume water during the protocol and the 15-minute rest period. The protocol used was different between males and females. The two main differences between protocols were the distance covered and the number of sprints completed. These protocols were previously described and used in another study that enrolled high level soccer players and found that it was an effective method of inducing fatigue (*Bello et al., 2019*).

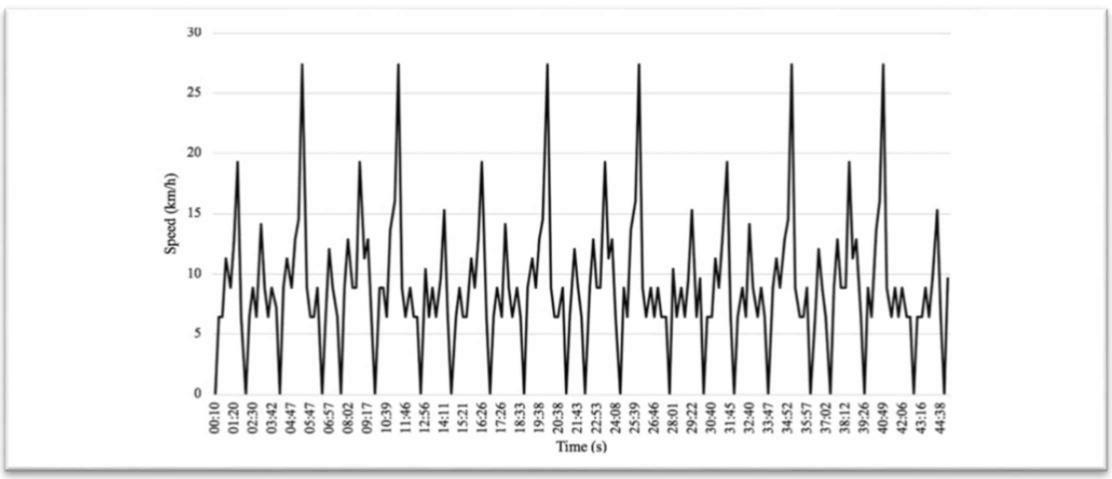

Figure 2.2 *Treadmill protocol*

2.4 STATISTICAL ANALYSIS

All variables measured on CMJ, DJ, SL CMJ AND SL DJ were assessed via paired t-test pre vs post. Asymmetry Index was calculated to determine degree of asymmetry by taking the difference between the left and the right leg divided by the value for the left leg. Asymmetry Index was applied for unilateral CMJ and DJ as well was for differences between legs on the strength test. Fatigue Index was calculated to determine degree of fatigue post-intervention by subtracting the pre and post values of each leg, and then dividing it by the pre-intervention value. Statistical significance was set at $\alpha=0.05$. Statistical analysis was performed using the statistical software R (*Version 4.2.0*)

CHAPTER 3

RESULTS

3.1 PARTICIPANTS

From the forty participants that were originally enrolled, thirty-eight completed the study and were included in the final analysis. Participant baseline characteristics obtained by the Bod Pod are shown in Table 3.1 and segmental lean analyses collected by the InBody at baseline are shown in Table 3.2. Two males dropped out from the study due to inability to attend all visits within the expected timeframe.

Table 3.1

Baseline characteristics

Measure	N (38)	Males (*n* = 18)	Females (*n* = 20)
Age (yrs)	21.2 ± 1.8	21.5 ± 1.6	20.9 ± 2.1
Height (cm)	173.3 ± 9.0	180.1 ± 6.8	167.2 ± 5.9
Weight (kg)	69.7 ± 10.7	76.8 ± 8.3	63.4 ± 8.4
BMI (kg/m^2)	23.1 ± 2.0	23.7 ± 1.9	22.6 ± 2.1
% BF	15.8 ± 6.2	10.7 ± 3.5	20.4 ± 4.3
90% of 5RM SL Leg Press – Right (kg)	81.6 ± 34.6	102.6 ± 31.4	62.8 ± 25.6
90% of 5RM SL Leg Press – Left (kg)	79.7 ± 34.7	99.3 ± 33.6	62.0 ± 25.5
Soccer Experience (yrs)	14.8 ± 3.5	14.1 ± 3.9	15.6 ± 2.9

Data shown as mean ± SD.

Table 3.2

Segmental Lean Analysis - InBody

Lower Extremity	N (38)	Males (*n* = 18)	Females (*n* = 20)
LBM Right Leg (kg)	9.0 ± 1.7	10.4 ± 1.1	7.7 ± 1.1
LBM Left Leg (kg)	8.9 ± 1.7	10.3 ± 1.1	7.7 ± 1.0

Data shown as mean ± SD.

3.2 INTERNAL LOAD

Heart rate monitoring metrics are summarized on Table 3.2. Men were found to have a significantly greater average workload score compared to women. Figures 3.2a, 3.2b and 3.2c show the average time in minutes spent in each heart rate zone for the whole population, men and women, respectively.

Table 3.3

Internal Load – Polar Team Pro

Measure	N (31)	Males (*n* = 17)	Females (*n* = 14)
HR Max (bpm)	185 ± 11	180 ± 10	192 ± 10
Avg HR (bpm)	143 ± 14	146 ± 13	140 ± 15
HR Z-50% (min)	11 ± 6	10 ± 3	12 ± 8
HR Z-60% (min)	18 ± 14	14 ± 18	20 ± 10
HR Z-70% (min)	29 ± 11	34 ± 14	25 ± 8
HR Z-80% (min)	30 ± 16	36 ± 18	26 ± 14
HR Z-90% (min)	10 ± 14	7 ± 11	12 ± 15
Workload Score	303 ± 68	321 ± 58*	292 ± 74

Data shown as mean ± SD. * denotes statistical significance.

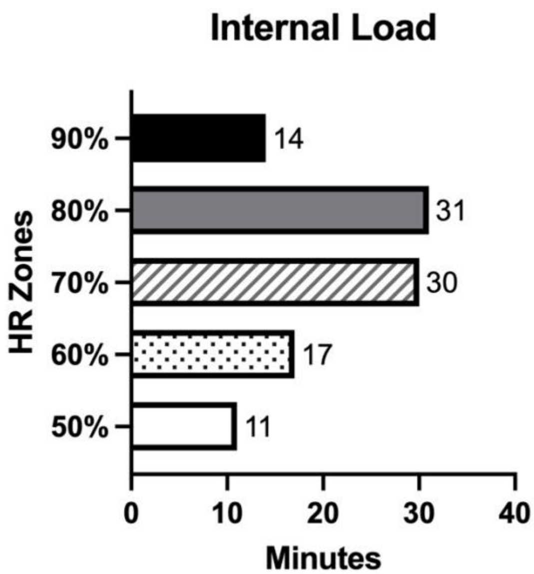

Figure 3.1 *Avg. time spent at HR Zones*

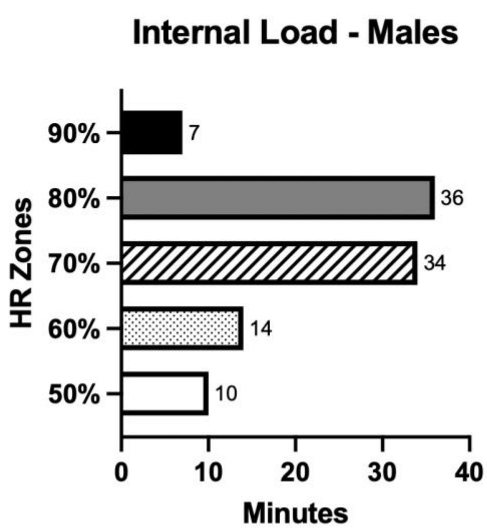

Figure 3.2 *Avg. time spent at HR Zones*

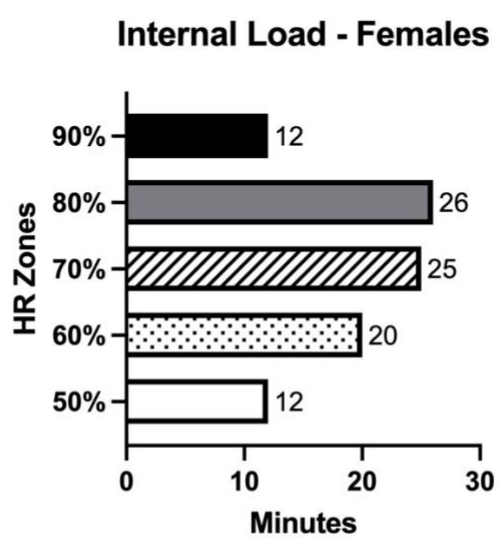

Figure 3.3 *Avg. time spent at HR Zones*

Table 3.4

Rating of Perceived Exertion

RPE		
	1st Half	2nd Half
N (38)	13 ± 1.7	14 ± 2.7
Males (*n*=18)	13 ± 1.8	14 ± 2.9
Females (*n*=20)	12 ± 1.5	13 ± 2.5

Data shown as mean ± SD.

3.3 PERFORMANCE METRICS

Jump Height

Force Plates: There was a significant decrease ($p<0.05$) in all CMJ, both bilateral and single leg jumps and, in the DJ, and a highly significant decrease in SL DJ in both legs was found. In men, there was a significant difference in all CMJs, and a meaningful decrease in SL DJs. On the other hand, significant differences were only detected in SL DJs in women. In addition, only a significant asymmetry index was found in bilateral DJs.

Table 3.5

Jump Height (cm) - Force Plates			
Test	Pre	Post	p-value
CMJ	32.0 ± 6.6	30.5 ± 6.1	0.0145*
SL CMJ (R)	15.8 ± 3.7	15.0 ± 4.0	0.0309*
SL CMJ (L)	16.0 ± 3.5	15.1 ± 3.5	0.0075*
DJ	30.7 ± 8.2	28.5 ± 8.2	0.0199*
SL DJ (R)	8.9 ± 3.7	6.7 ± 3.4	<0.001
SL DJ (L)	8.3 ± 3.5	6.6 ± 3.4	<0.001

Data shown as mean ± SD. * and/or p<0.001 denotes statistical significance.

Table 3.6

Jump Height (cm) – Sex Comparison (FP)						
	Males			Females		
Test	Pre	Post	p-value	Pre	Post	p-value
CMJ	37.2 ± 5.1	34.7 ± 5.4	0.0193*	27.3 ± 3.3	26.9 ± 3.9	0.396
SL CMJ (R)	18.7 ± 2.7	17.4 ± 3.7	0.045*	13.1 ± 2.4	12.9 ± 2.9	0.411
SL CMJ (L)	18.5 ± 2.4	17.1 ± 3.2	0.0202*	13.6 ± 2.4	13.3 ± 2.6	0.160
DJ	32.5 ± 12.5	29.6 ± 12	0.1038	27.6 ± 5.1	26.0 ± 5.7	0.083
SL DJ (R)	9.1 ± 4.6	7.1 ± 4.4	<0.001	7.5 ± 3.0	6.0 ± 2.6	<0.001
SL DJ (L)	8.6 ± 4.5	6.5 ± 3.9	0.00142*	7.6 ± 2.9	6.4 ± 3.3	0.004*

Data shown as mean ± SD. * and/or p<0.001 denotes statistical significance.

Jump Mat: Data obtained from the jump mat showed a meaningful decrease in the CMJ, SL CML on the left leg and in SL DJ on the right leg for the whole population and in males. No significant difference was found in females. Moreover, no significant asymmetry index was detected.

Table 3.7

Jump Height (cm) - Jump Mat			
Test	Pre	Post	p-value
CMJ	47.5 ± 8.4	45.7 ± 7.9	0.0395*
SL CMJ (R)	28.2 ± 5.3	27.4 ± 5.5	0.1137
SL CMJ (L)	28.5 ± 4.7	27.4 ± 4.3	0.0298*
DJ	47.5 ± 7.0	46.5 ± 6.7	0.1048
SL DJ (R)	27.9 ± 5.3	26.9 ± 5.5	0.0181*
SL DJ (L)	28.5 ± 4.6	27.4 ± 4.0	0.0965

Data shown as mean ± SD. * denotes statistical significance.

Table 3.8

Jump Height (cm) – Sex Comparison (JM)						
	Males			Females		
Test	Pre	Post	p-value	Pre	Post	p-value
CMJ	54.2 ± 6.9	50.9 ± 8.0	0.0193*	41.3 ± 3.5	41.1 ± 4.1	0.396
SL CMJ (R)	32.1 ± 4.6	30.9 ± 5.4	0.045*	24.9 ± 3.2	24.3 ± 3.4	0.411
SL CMJ (L)	31.9 ± 3.5	29.9 ± 3.9	0.0202*	25.3 ± 3.1	25.2 ± 3.3	0.160
DJ	53.4 ± 4.7	51.6 ± 5.5	0.1038	42.1 ± 3.3	42.1 ± 3.7	0.083
SL DJ (R)	31.4 ± 3.4	29.7 ± 3.7	<0.001	24.9 ± 3.3	24.5 ± 3.9	<0.001
SL DJ (L)	30.7 ± 3.6	29.2 ± 3.3	0.00142*	25.3 ± 3.8	25.2 ± 3.7	0.004*

Data shown as mean ± SD. * denotes statistical significance.

Table 3.9

Asymmetry Index - SLCMJ								
	Males				Females			
	Pre	Post	% Diff	p-value	Pre	Post	% Diff	p-value
FP	8.55 ± 5.68	9.79 ± 6.77	1.24	0.332	10.4 ± 9.27	10.8 ± 10.9	0.4	0.788
JM	6.07 ± 4.56	9.87 ± 14.6	3.8	0.292	5.70 ± 4.51	6.24 ± 5.66	0.54	0.608

Data shown as mean ± SD. * denotes statistical significance.

Table 3.10

Fatigue Index – SLCMJ								
	Males				Females			
	Right	Left	% Diff	p-value	Right	Left	% Diff	p-value
FP	6.92 ± 13.9	7.61 ± 12.8	0.69	0.752	2.58 ± 12.6	2.25 ± 6.85	-0.3	0.895
JM	3.1 ± 15.4	5.81 ± 9.84	2.75	0.402	2.53 ± 7.04	0.21 ± 5.15	-2.3	0.046*

Data shown as mean ± SD. * denotes statistical significance.

Table 3.11

Asymmetry Index - SLDJ								
	Males				Females			
	Pre	Post	% Diff	p-value	Pre	Post	% Diff	p-value
FP	15.9 ± 13.5	28.5 ± 26.6	12.6	0.332	22.6 ± 22.9	4.24 ± 64.3	-18.36	0.788
JM	6.35 ± 9.99	5.22 ± 3.61	1.13	0.665	7.38 ± 6.24	6.70 ± 6.95	-0.68	0.608

Data shown as mean ± SD. * denotes statistical significance.

Table 3.12

Fatigue Index – SLDJ								
	Males				Females			
	Right	Left	% Diff	p-value	Right	Left	% Diff	p-value
FP	21.9 ± 20.1	20.9 ± 30	-1.0	0.856	18.9 ± 20.6	17.5 ± 28.0	-1.4	0.738
JM	5.48 ± 8.04	4.06 ± 12.1	-1.4	0.577	1.30 ± 9.32	0.35 ± 8.09	-1	0.582

Data shown as mean ± SD. * denotes statistical significance.

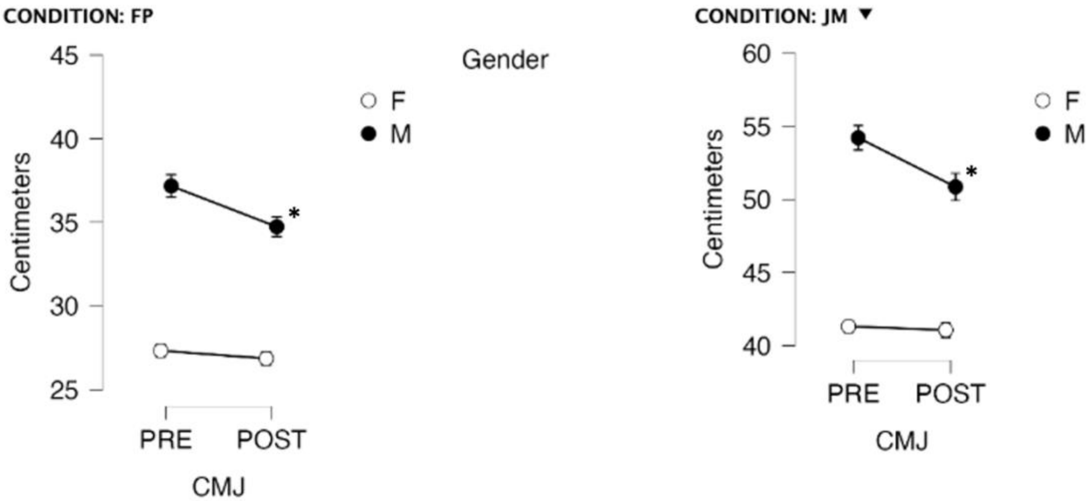

Figure 3.4 *Comparison of jump heights pre- vs post- exercise-induced fatigue protocol in the CMJ in FP and JM.* *: Indicates significant decrease from pre-test (P<0.05).

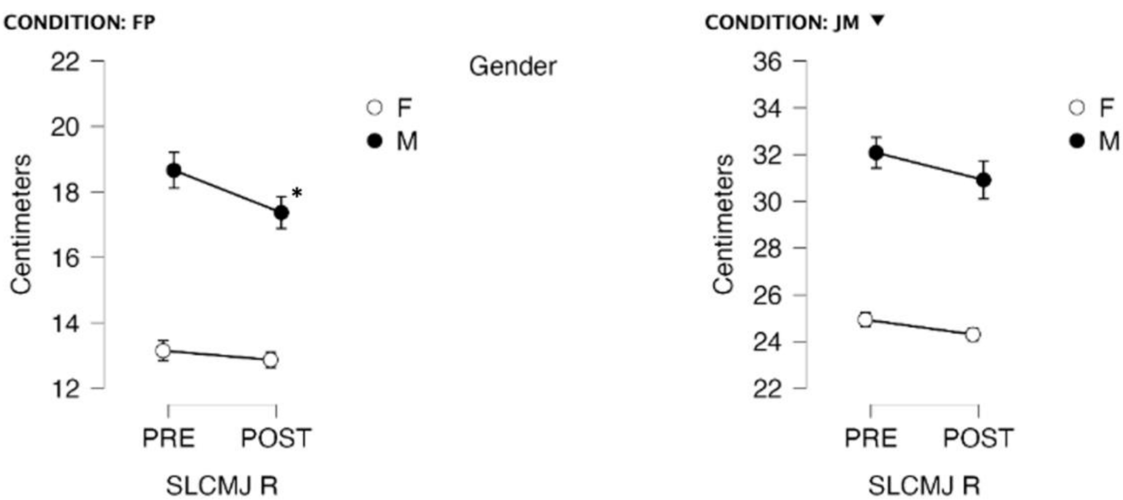

Figure 3.5 *Comparison of jump heights pre- vs post- exercise-induced fatigue protocol in the SLCMJ (R) in FP and JM.* *: Indicates significant decrease from pre-test (P<0.05).

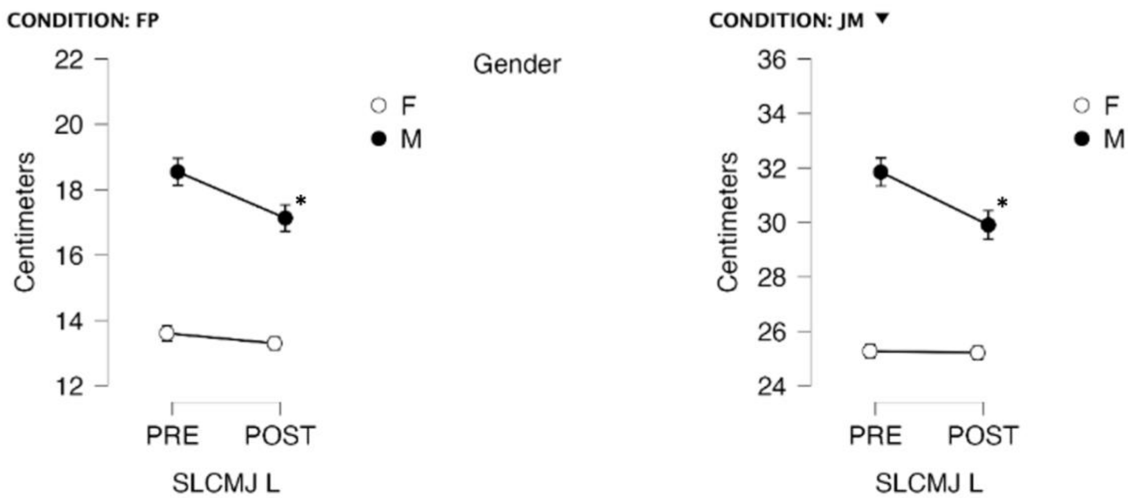

Figure 3.6 *Comparison of jump heights pre- vs post- exercise-induced fatigue protocol in the SLCMJ (L) in FP and JM.* *: Indicates significant decrease from pre-test (P<0.05).

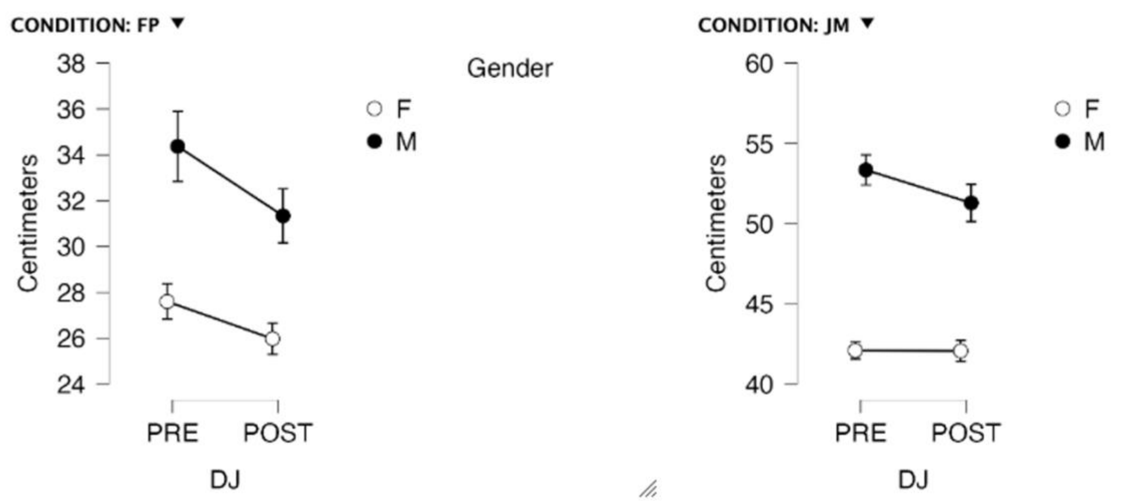

Figure 3.7 *Comparison of jump heights pre- vs post- exercise-induced fatigue protocol in the DJ in FP and JM.* *: Indicates significant decrease from pre-test (P<0.05).

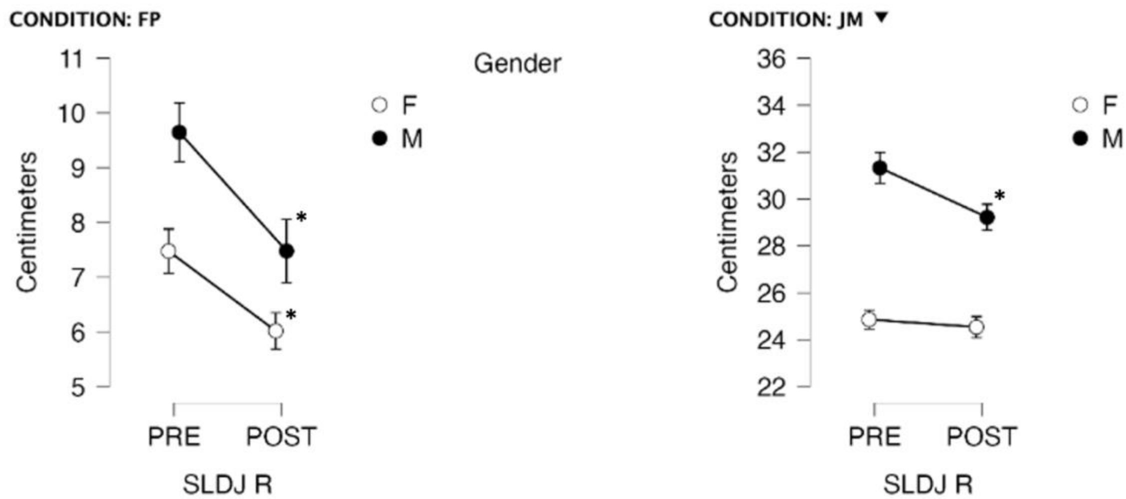

Figure 3.8 *Comparison of jump heights pre- vs post- exercise-induced fatigue protocol in the SLDJ (R) in FP and JM.* *: Indicates significant decrease from pre-test ($P<0.05$).

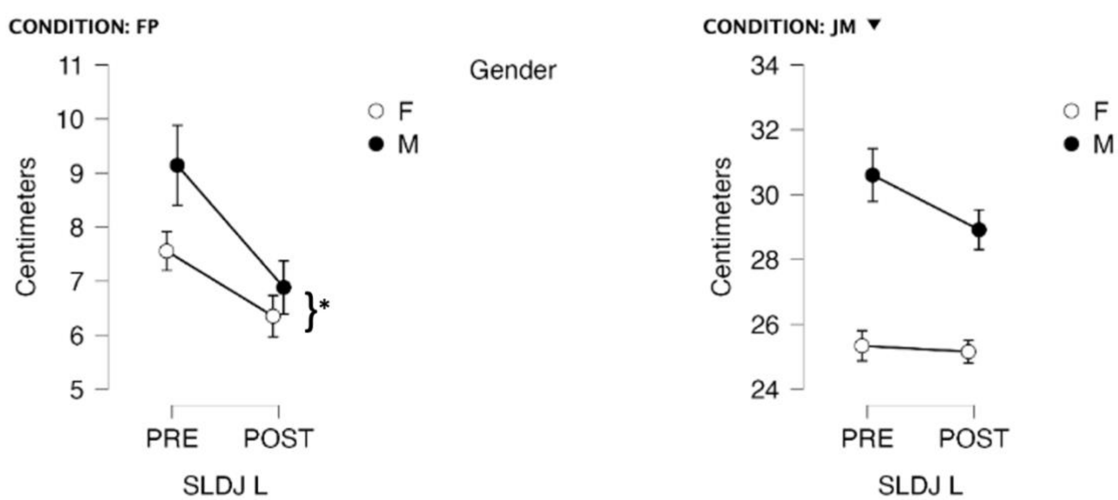

Figure 3.9 *Comparison of jump heights pre- vs post- exercise-induced fatigue protocol in the SLDJ (L) in FP and JM.* *: Indicates significant decrease from pre-test ($P<0.05$).

RSI and mRSI

A significant decrease in RSI on the SL DJ on the right leg was for all participants. No significant differences were detected for females or asymmetry index. On the other hand, there was significant decrease of mRSI in all type of jumps except for SL CMJ on the right leg for all participants. Males had a significant decrease in CMJ, SL CMJ on the left leg and both SL DJ. The only significant effect found in females was on both SL DJ. No significant decrease was noticed for RSI asymmetry index.

Table 3.13

Reactive Strength Index (RSI)					
Test	Pre	Post	p-value	Males p-value	Females p-value
CMJ	0.64 ± 0.12	0.61 ± 0.12	0.0644	0.0564	0.6378
SL CMJ (R)	0.42 ± 0.08	0.41 ± 0.10	0.7796	0.3438	0.7375
SL CMJ (L)	0.43 ± 0.10	0.41 ± 0.10	0.1053	0.0673	0.5931
DJ	1.16 ± 0.32	1.13 ± 0.29	0.1829	0.097	0.8364
SL DJ (R)	0.78 ± 0.21	0.74 ± 0.22	0.0338*	0.0403*	0.3823
SL DJ (L)	0.77 ± 0.21	0.73 ± 0.21	0.0514	0.1678	0.1875

Data shown as mean ± SD. * denotes statistical significance.

Table 3.14

RSI Asymmetry Index					
Test	Pre	Post	p-value	Males p-value	Females p-value
CMJ	0.107 ± 0.097	0.081 ± 0.082	0.1287	0.1321	0.6133
DJ	0.095 ± 0.079	0.078 ± 0.068	0.1812	0.1896	0.6805

Data shown as mean ± SD.

Table 3.15

Modified Reactive Strength Index (mRSI)					
Test	Pre	Post	p-value	Males p-value	Females p-value
CMJ	0.39 ± 0.12	0.37 ± 0.12	0.0113*	0.0148*	0.3829
SL CMJ (R)	0.17 ± 0.05	0.17 ± 0.05	0.1827	0.0501	0.9392
SL CMJ (L)	0.18 ± 0.05	0.17 ± 0.05	0.0377*	0.0271*	0.5369
DJ	0.72 ± 0.30	0.64 ± 0.24	0.0095*	0.0488	0.0962
SL DJ (R)	0.18 ± 0.09	0.14 ± 0.08	p<0.001	p<0.001	p<0.001
SL DJ (L)	0.18 ± 0.09	0.14 ± 0.09	p<0.001	0.0023*	0.0135*

Data shown as mean ± SD. * and/or p<0.001denotes statistical significance.

Table 3.16

mRSI Asymmetry Index					
Test	Pre	Post	p-value	Males p-value	Females p-value
CMJ	0.144 ± 0.122	0.117 ± 0.106	0.1249	0.1214	0.6465
DJ	0.235 ± 0.233	0.387± 0.646	0.08389	0.2778	0.1456

Data shown as mean ± SD.

Asymmetry on Average Propulsive Force

No significant differences were found for rate of force production in any of the jumps.

Table 3.17

Asymmetry L|R Avg. Propulsive Force (%)					
Test	Pre	Post	p-value	Males p-value	Females p-value
CMJ	-1.32 ± 3.69	-1.45 ± 4.87	0.752	0.8997	0.5645
DJ	-1.99 ± 4.53	-2.6 ± 5.06	0.2893	0.2631	0.739

Data shown as mean ± SD.

Strength Testing

There was a highly significant decrease in the number of repetitions performed at 90% of 5RM in both legs for the whole population. Both males and females presented similar reduction of repetitions on both legs. No significant difference was found on the asymmetry index.

Table 3.18

Number of Reps on SL Leg Press @90% of 5RM			
Lower Limb	Pre	Post	p-value
Right Leg	14 ± 6.0	11.2 ± 5.8	p<0.001
Left Leg	13.6 ± 6.2	10.6 ± 6.2	p<0.001

Data shown as mean ± SD. * and/or p<0.001 denotes statistical significance.

Table 3.19

Number of Reps on SL Press – Sex Comparison						
	Males			Females		
Lower Limb	Pre	Post	p-value	Pre	Post	p-value
Right Leg	15.2 ± 7.5	11.7 ± 6.4	0.0022*	12.9 ± 4.1	10.9 ± 5.3	0.043*
Left Leg	14.1 ± 7.9	10.2 ± 7.3	p<0.001	13.1 ± 4.4	10.9 ± 5.1	0.037*

Data shown as mean ± SD. * and/or p<0.001 denotes statistical significance.

Table 3.20

Asymmetry Index – SL Press							
Males				Females			
Pre	Post	% Diff	p-value	Pre	Post	% Diff	p-value
26.5 ± 31.1	36.7 ± 37.5	10.2	0.3109	19.9 ± 15.7	23.1 ± 20.3	3.2	0.5804

Data shown as mean ± SD. * denotes statistical significance.

Table 3.21

Fatigue Index – Leg Press							
Males				Females			
Right	Left	% Diff	p-value	Right	Left	% Diff	p-value
20.8 ± 29.0	29.1 ± 26.9	8.4	0.094	15.7 ± 26.3	15.0 ± 29.8	-0.7	0.873

Data shown as mean ± SD. * denotes statistical significance.

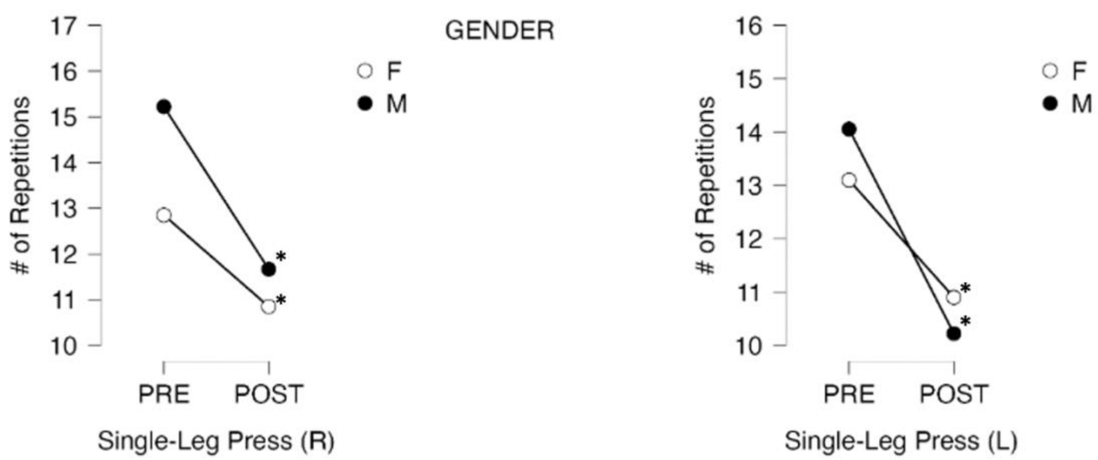

Figure 3.10 *Comparison of repetitions completed on the single leg press pre- vs post-fatiguing protocol.* *: Indicates significant decrease from pre-test (P<0.05).

CHAPTER 4

DISCUSSION

The purpose of this study was to analyze the inter-limb functional asymmetries in strength and power in the lower limbs after a 90-minute simulated game on a treadmill. After a fatiguing bout of exercise that simulated exercise demands of soccer on a treadmill, shorter jump heights were seen in all types of jumps in comparison to pre jump height assessments, and leg press repetitions decreased from pre to post assessments. Jumps completed on the force platforms were found to have a significant decrease post fatiguing protocol. On the other hand, only CMJ, SLCMJ (L) and SLDJ (R) recorded on the JMs were the assessments that demonstrated significant decreases in jump performance. When looking at these results by gender, men displayed significant reductions in all jumps, and surprisingly, both FP and JM presented similar reductions in the DJs. JM was as effective as the FP on detecting those power imbalances in most of the jumps. Interestingly, only women were found to have significant differences in SLDJ on FP and no significant differences were detected in JM. These reductions in jump performance were similar to previous studies in the literature that used the CMJ and DJ as assessments in comparable athletic populations (Bell et al., 2014, Bishop et al., 2018). Furthermore, asymmetry index was only significant in DJ performance. Based on these outcomes, fatigue negatively affected performance and power production capabilities in the vertical jump as well as in the DJ.

Besides the exacerbation in power asymmetries in the vertical jump, strength capabilities were also reduced. A significantly lower number of repetitions on the SL press at 90% of 5RM was found after the fatiguing protocol, similar to reductions in strength performance were seen in the systematic review performed by Bishop et al. in 2018. Both sexes exhibited significant reductions in strength as well. Men displayed highly significance ($p<0.001$) differences in the total amount of repetitions performed with the left leg.

Other metrics utilized to analyze power asymmetries and fatigue were RSI and mRSI. Even though RSI has been used more frequently in research because it can be calculated using the JM as well, mRSI is becoming more popular in studies because of the increased accessibility to force platforms. Both RSI and mRSI have been demonstrated to be a valid and reliable metrics, especially in the context of performance monitoring and seasonal fatigue (Bishop et al., 2022). Our results showed that mRSI was significantly lower post fatiguing protocol in all jumps, except in the SLCMJ on the right leg. Men displayed a significantly lower mRSI in CMIJ and SLCMJ on the left leg and a highly significantly lower mRSI in the SLDJ. Women only presented meaningful decreases in mRSI in SLDJ. Alternatively, differences in RSI were only statistically significant in the SLDJ on the right leg in the whole population, and in male participants only. These results indicates that SLDJ may be more sensitive to changes under fatigue and mRSI is able to detect more subtle changes in contrast to RSI. Reduced RSI and mRSI values are correlated with decreased jump heights. These metrics are also indicators of fatigue; and since all jumps were found to have reductions in vertical displacement, we can infer that the treadmill protocol was successful in inducing fatigue.

The protocol was found to be more taxing for men than women due to the higher reported RPE scores as well as the higher workload scores obtained from the heart rate monitor. This could explain the sex differences seen in asymmetry rates in this study.

Based on the adverse power and strength outcomes after a 90-minute simulated game on the treadmill, fatigue appears to exacerbate asymmetries in lower limbs. Overall reductions in jump heights, RSI and mRSI values, and maximal repetitions on the leg press suggest that sport performance declined in both men and women after a fatiguing exercise bout. Despite previous work conducted by McFadden et al. in 2020 demonstrating no significant differences in physical demands in soccer players between men and women, men displayed a significantly higher workload than women, however, the protocol used in this study was different between sexes. On average, a higher workload score and greater amount of time spent in heart rate zones 3 and 4 were seen in men compared to women. The higher workloads could potentially explain why men had more significant changes in jump and strength test performances. Participant experience in the sport is also a potential variable that could have influenced these findings. Women presented approximately one year and five months more of experience than men at baseline. Additionally, most of the women were part of a DI soccer team whereas most of the men participants were part of lower divisions collegiate teams. According to McKay et al., division one athletes are considered part of the tier 4: elite/international level in their participant classification framework (McKay et al., 2021). In this case, because of the men who participated in this study are mostly considered part of a lower tier on this categorization, their strength training regimen and level of competition at the collegiate level could also explain some of the sex differences.

The use of a sport-specific fatiguing protocol is one of the strengths of this study. Other studies have used fatiguing protocols that successfully have induced fatigue, but the exercise modality does not truly replicate the exercise intensities of a given sport. It is crucial to implement protocol that simulate the unique physical demands to truly identify the risk of injury and the reduction in performance due to inter-limb asymmetries under the influence of fatigue. In addition, another major strength is the sample size of the population. Thirty-eight participants and almost an even distribution between men and women is a bigger sample size than most studies in the literature which offers more precise estimation of the soccer player population. In terms of the limitations, the variability of the participants between men and women could have potentially affected the outcomes of this experiment. Even though all participants met the inclusion criteria, men presented greater variability on the collegiate level that they play compared to the women. All participants were considered high level soccer players, however, the experience and intensity of the game in which they compete can also be a factor that altered the results of this study.

In conclusion, an exercised-induced fatiguing protocol that simulated the physical demands of a soccer match for 90 minutes did negatively affect power and strength asymmetries in the lower limbs in high level soccer players which agrees with the proposed hypothesis. Despite the fact that women tend to be more prone to lower body injuries, men were more sensitive to changes in inter-limb asymmetries for strength and power due to the induced fatigue and the significant greater workloads. Women were not found to have worse asymmetry rates than men, which is incongruent with our second hypothesis in this study. In terms of practical applications, the use of force plates or jump mats to measure inter-limbs asymmetries is very advisable. Force platforms are becoming the most preferable piece of equipment used for coaches and researchers. Even though force plates are becoming more accessible and have been more used in research, they are still an expensive piece of equipment that limits many practitioners and coaches from their use. However, the results obtained in this study demonstrated that jump mats are an effective tool to detect asymmetries and it is a more user friendly and cost-effective type of technology. More research is needed to develop standardized and effective methods to measure inter-limb asymmetries and to be able to draw firm conclusions about their effects on sport performance.

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